

# INSPECTIONS AND SITE VISITS

All aspects of a public water system (water source, treatment facility, operation and maintenance) need periodic inspection to assure that the water system continues to supply safe drinking water to the public.

## WATER SYSTEM INSPECTIONS

During 2012, HEALTH's, DWQ staff conducted sanitary survey inspections as listed in the detailed chart provided. Follow-up sanitary survey inspections were required at a majority of these facilities to ensure that any deficiencies had been satisfactorily addressed. Additional inspections were conducted in direct response to requests for technical assistance from water systems. Survey personnel also performed compliance inspections of new construction or significant improvements in water system infrastructure.

Our goal is to perform a sanitary survey every 3-years for all community water systems and every 5-years for all others.

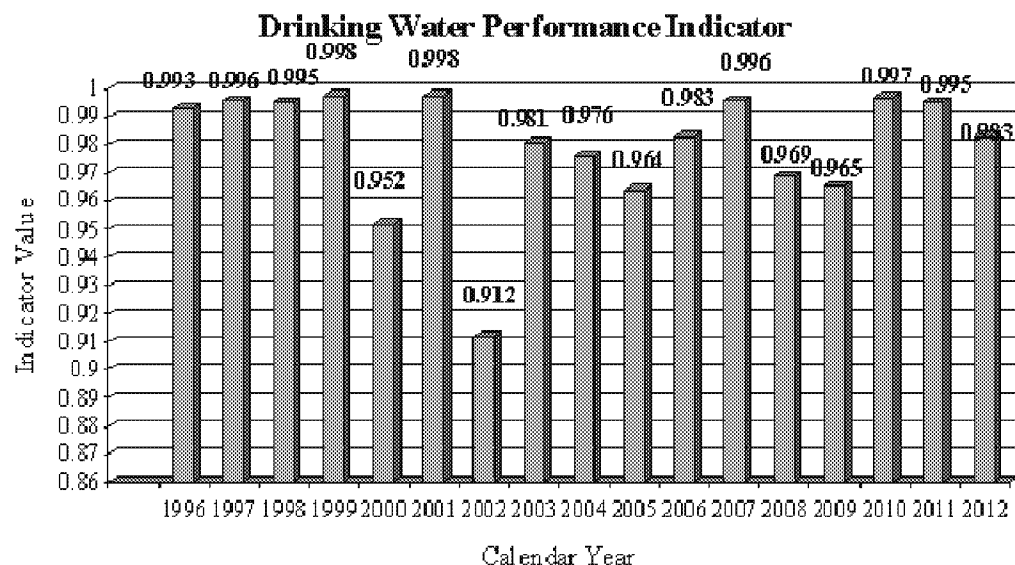
Water System Inspections	2012
Total number of Water systems inspected	103
Total population served	199,168
Number of community systems inspected	30
Population served	183,828
Number of transient Non-community systems Inspected	60
Population Served	12,245
Number of Non-transient, non-community systems inspected	13
Population Served	3,095

# PERFORMANCE REVIEW

Of all the requirements with which water systems are expected to comply, the most important is that of meeting minimum health standards. Each year, HEALTH evaluates the progress of the State's individual water systems as well as Rhode Island's Drinking Water Program in meeting these minimum health standards.

## PERFORMANCE REVIEW

In making this evaluation, HEALTH uses a "performance indicator value," based on compliance with the Safe Drinking Water Act requirements for the entire year. The indicator value, shown to the right, is based on compliance with maximum contaminant levels (MCLs) and treatment technique requirements. Violations related to public education/public notice and monitoring errors are not included in this indicator. To make the indicator more representative of the state's drinking water quality, it is weighted by the number of days the system operated in compliance, the size of the population served by the water system, and the total number of days that the system was actually in operation. An indicator value of 1.0 would mean that all public water systems were in compliance with every MCL and treatment technique requirement for the entire year.



$$\text{Indicator Value} = \frac{\sum (\text{PWS Population Served}) \times (\text{Days in Compliance With MCLs and Treatment Technique Requirements})}{\sum (\text{PWS Population Served}) \times (\text{Total Days in Operation})}$$

# PERFORMANCE REVIEW

## COMPLIANCE

Compliance data is included herein for calendar year 2012. The 2012 Annual Compliance Report summary table, as required by the Safe Drinking Water Act amendments of 1996, can be found in Appendix – II (page 36).

During calendar year 2012, 147 violations of the Safe Drinking Water Act were reported by 122 of the State's public water systems. Of these 146 violations, 56 were water quality violations, 86 were monitoring violations, one was a treatment technique violation, one was a CCR reporting violation, two were public notification violations and one was a failure to provide public education. A summary of the violations is presented in Appendix – I (page 30).

### Quality Violations

Quality violations occur when the monitoring results for a particular contaminant exceed the drinking water standard within a specific time period. Public water systems must monitor for 90 contaminants including inorganic compounds, volatile organic compounds, synthetic organic compounds, radionuclides, and pathogens.

During 2012, 44 of the public systems exceeded a drinking water standard for a total of 56 violations. Of those 56 violations, 52 were bacteriological violations, one was for nitrate, and 35 were for trihalomethanes (TTHM).

### Monitoring Violations

Monitoring violations occur when a water system fails to perform the required monitoring for a particular contaminant within a specified time period and/or fails to report the results by the tenth of the following month, as required. During 2012, 73 of the state's water systems failed to perform the required monitoring and/or reporting within the specified time period. In all, 86 monitoring and reporting violations were reported.

### Public Notification Violations

Public notification violations occur when a water system fails to perform the public notification within the required time period. During 2012, two water systems failed to perform public notification

# PERFORMANCE REVIEW

## Public Education Violations

Public education violations occur when a water system fails to perform the required public education within the required time period. During 2012, one water system failed to perform public education within the required time period.

## Consumer Confidence Report Violations

Consumer confidence report violations occur whenever a community public water system fails to provide a consumer confidence report (CCR) to their consumers by July 1 of each calendar year, and/or fails to submit a CCR certification form to the Department of Health by October 1 of each calendar year. During 2012, one public water system failed to provide a consumer confidence report as required.

## Treatment Technique Violations

Treatment Technique violations occur when a water system fails to comply with the required treatment. During 2012, one of the state's water systems failed to maintain proper treatment as required.



# COMMUNITY WATER SYSTEMS

<b>Quality:</b>	
CANONCHET CLIFFS WATER ASSOCIATION INC. (TCR)	2
NVAL STATION NEWPORT (TTHM)	2
NEWPORT, CITY OF (TTHM)	1
PASCOAG UTILITY DISTRICT, WATER DEPARTMENT (TCR)	1
SHADY HARBOR FIRE DISTRICT (TCR)	1
SOUTH KINGSTOWN SOUTH SHORE (TCR)	1
WESTERLY WATER DEPARTMENT (TCR)	1
<b>Monitoring:</b>	
CENTRAL BEACH FIRE DISTRICT (WQP)	1
CUMBERLAND, TOWN OF (GWR)	1
HEMLOCK VILLAGE (PB&CU)	1
JAMESTOWN WATER DEPARTMENT (ASBESTOS)	1
JOHNSTON WATER CTRL FAC – WEST END (ASBESTOS)	1
LINDHBROOK WATER COMPANY (PB&CU)	3
MAPLEHILL MOBILE HOME PARK (ASBESTOS)	1
NAVAL STATION NEWPORT (PB&CU)	1
TOWN OF NORTH KINGSTOWN (SOC)	1
QUONOCONTAUG EAST BEACH WATER ASSOCIATION (TCR)	1
QUONOCONTAUG EAST BEACH WATER ASSOCIATION (GWR)	1
RICHMOND WATER SUPPLY BOARD (TCR)	1
RICHMOND WATER SUPPLY BOARD (PB&CU)	1
SMITHFIELD WATER SUPPLY BOARD (ASBESTOS)	1
STONE BRIDGE FIRE DISTRICT (DBP-TOTAL CARBON)	1
THE VILLAGE ON CHOPMIST HILL (PB&CU)	1
UNITED STATES NAVY (FORT ADAMS) (PB&CU)	1
UNITED WATER RHODE ISLAND (GWR)	1
WESTERLY WATER DEPARTMENT (TCR)	2
WESTERLY WATER DEPARTMENT (GWR)	1
WOODPECKER HILL NURSING HOME (PB&CU)	1

# COMMUNITY WATER SYSTEMS

## VIOLATIONS 2012

NUMBER OF  
VIOLATIONS

<b>Consumer Confidence Report:</b>	
CENTRAL BEACH FIRE DISTRICT	1
<b>Public Education:</b>	
HEBERT NURSING HOME (TCR)	1
PRUDENCE ISLAND WATER DISTRICT (PB&CU)	1
<b>Treatment Technique:</b>	
PASCOAG UTILITY DISTRICT, WATER DIVISION (GWR)	1
COMMUNITY WATER SYSTEM, SUBTOTAL	37

# NON-COMMUNITY NON-TRANSIENT WATER SYSTEMS

## VIOLATIONS 2012

	NUMBER OF VIOLATIONS
<b>Quality:</b>	
CHOPMIST HILL COMMUNITY CENTER (TCR)	1
PINEWOOD PARK SCHOOL (TCR)	1
SILVEIRA KINDERGATREN AND NURSERY (TCR)	1
WEST GLOCESTER ELEMENTARY SCHOOL (TCR)	1
<b>Monitoring and Reporting:</b>	
CHARIHO REGIONAL SCHOOL (PB&CU)	5
CHARIHO MIDDLE SCHOOL (PB&CU)	1
CHARLESTOWN POLICE STATION (PB&CU)	1
DR. DAYCARE CHILD DEVELOPMENT CENTER (TCR)	1
FACTORY MUTUAL (TCR)	1
FACTORY MUTUAL (GWR)	1
NORTH SCITUATE ELEMENTARY SCHOOL (GWR)	1
<b>Public Education:</b>	
CHARIHO REGIONAL HIGH SCHOOL(PB&CU)	1
<b>Treatment Technique:</b>	
NORTH SCITUATE ELEMENTARY SCHOOL (GWR)	1
NON-COMMUNITY NON-TRANSIENT WATER SYSTEM SUBTOTAL	17

# TRANSIENT WATER SYSTEMS (CONTINUED)

## VIOLATIONS 2012

NUMBER OF  
VIOLATIONS

Quality:	
ALLIES DONUTS, INC. (TCR)	3
ASHAWAY LINE & TWINE MFG. CO. UPPER MILL (TCR)	1
BURLINGAME RESERVATION-MAIN CAMP LEGIONTOWN (TCR)	1
CAMP RUSSELL – PUMP HOUSE MALLARD SHORES (TCR)	1
CHESTERS (TCR)	2
D.B. MART #9 (TCR)	2
EAST BEACH LANDING CONDOMINIUMS (TCR)	2
EXETER PUBLIC LIBRARY (TCR)	1
EZ MART #4 (TCR)	1
FAMOUS PIZZA (TCR)	1
FENNER GOLF CLUB, LLC (TCR)	1
FREDERICK J. BENSON TOWN BEACH (TCR)	1
FRONTIER CAMPER PARK (TCR)	1
GRAYS ICE CREAM (TCR)	1
GREENWOOD HILL CAMPGROUND ASSOCIATION (TCR)	1
K & S PIZZA (TCR)	2
NEW ENGLAND FARMS (TCR)	2
NORDIC LODGE (TCR)	1
OAK EMBERS CAMPGROUND (TCR)	1
PEABODY'S BEACH (TCR)	2
PLAZA AT PARK SQUARE (TCR)	6
SOUTH SHORE MENTAL HEALTH (TCR)	2
STONE HOUSE MOTOR INN (TCR)	1
STEPPING STONE STABLES (NO3)	1
TOWNSMEN CLUB (TCR)	1
TWIN MAPLES (TCR)	1
WESTWOOD YMCA (TCR)	1
WINDMILL HILL GOLF COURSE, INC. (TCR)	1

# VIOLATIONS 2012

NUMBER OF  
VIOLATIONS

## TRANSIENT WATER SYSTEMS (CONTINUED)

<b>Monitoring and Reporting:</b>	
AMERICAN LEGION-GORDON GREENE POST #27 (TCR)	1
BURLINGAME RESERVATION-MAIN CAMP-LEGIONTOWN (TCR)	1
BURLINGAME RESERVATION-MAIN CAMP-LEGIONTOWN (GWR)	1
CAROUSEL MARKETPLACE (NO3)	1
CORNERSTONE PUB (TCR)	1
COVENTRY MENS CLUB (NO3)	1
COVENTRY MENS CLUB (NO2)	1
D.B. MART (TCR)	3
D.B.MART (NO3)	1
D.R. MOTEL ENTERPRISES, INC. (TCR)	1
EZ MART (TCR)	2
FAMOUS PIZZA (TCR)	1
FENNER HILL GOLF CLUB LLC. (TCR)	1
FOSTER COUNTRY CLUB (TCR)	2
FRONTIER CAMPER PARK (GWR)	1
HOG ISLAND WATER ASSOCIATION-SOUTH END (TCR)	1
K&S PIZZA (GWR)	1
MICHAELS SHELL STATION (TCR)	1
NATIONWIDE DIESEL TECHNOLOGIES INC. (TCR)	1
NEWPORT BOYS AND GIRLS CLUB (TCR)	1
NORMAN & PAMELA MACHON DBA SOPHIES COFFEE (TCR)	2
NUTZ (TCR)	1
OUR LADY OF GOOD HELP (NO3)	1
OUR LADY OF GOOD HELP (NO2)	1
ROCKY MOUNTAIN SPRING WATER – ARMISTICE (NO2)	1
ROCKY MOUNTAIN SPRING WATER-FRONT STREET (NO2)	1
ROCKY MOUNTAIN SPRING WATER-PAWTUCKET (NO2)	1
SALT POND SETTLEMENT CONDO ASSOCIATION (TCR)	1
TROPIC FROST (TCR)	1
TROPIC FROST (NO3)	1
TROPIC FROST (NO2)	1
U.S. FISH AND WILDLIFE SERVICE VISITOR CTR (TCR)	1
W. ALTON JONES CAMPUS-ENVIRONMENTAL ED (TCR)	1
W. ALTON JONES CAMPUS-URI RESEARCH BUILDING (TCR)	1
W. ALTON JONES CAMPUS-URI-WHISPIRING PINES (TCR)	1

# TRANSIENT WATER SYSTEMS (CONTINUED)

## VIOLATIONS 2012

	NUMBER OF VIOLATIONS
W. ALTON JONES CAMPUS-MAIN OFFICE-FARM HOUSE (TCR)	1
WEST GREENWICH CONDO ASSOCIATION (TCR)	1
WEST KINGSTON PARK (TCR)	1
WESTWOOD YMCA (TCR)	1
WESTWOOD YMCA (GWR)	1
WINDMILL HILL GOLF COURSE, INC. (NO3)	1
WINDMILL HILL GOLF COURSE, INC. (NO2)	1
YMCA CAMP FULLER (TCR)	1
YMCA CAMP FULLER (GWR)	1
<b>Public Notification:</b>	
PEABODYS BEACH	1
Transient Water System, Subtotal	91

# APPENDIX II

## Compliance Table

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through

December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
	<b><u>Organic Contaminants</u></b>							
2981	1,1,1-Trichloroethane	0.2	0	0			0	0
2977	1,1-Dichloroethylene	0.007	0	0			0	0
2985	1,1,2-Trichloroethane	.005	0	0			0	0
2378	1,2,4-Trichlorobenzene	.07	0	0			0	0
2931	1,2-Dibromo-3-chloropropane (DBCP)	0.0002	0	0			0	0
2980	1,2-Dichloroethane	0.005	0	0			0	0
2983	1,2-Dichloropropane	0.005	0	0			0	0
2063	2,3,7,8-TCDD (Dioxin)	$3 \times 10^{-8}$	0	0			1	1
2110	2,4,5-TP	0.05	0	0			1	1
2105	2,4-D	0.07	0	0			1	1
2051	Alachlor	0.002	0	0			1	1

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
2050	Atrazine	0.003	0	0			0	0
2990	Benzene	0.005	0	0			2	2
2306	Benzo[a]pyrene	0.0002	0	0			1	1
2046	Carbofuran	0.04	0	0			1	1
2982	Carbon tetrachloride	0.005	0	0			0	0
2959	Chlordane	0.002	0	0			1	1
2380	cis-1,2-Dichloroethylene	0.07	0	0			0	0
2031	Dalapon	0.2	0	0			1	1
2035	Di(2-ethylhexyl)adipate	0.4	0	0			1	1
2039	Di(2-ethylhexyl)phthalate	0.006	0	0			1	1
2964	Dichloromethane	0.005	0	0			0	0
2041	Dinoseb	0.007	0	0			1	1
2032	Diquat	0.02	0	0			1	1



**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
2033	Endothall	0.1	0	0			1	1
2005	Endrin	0.002	0	0			1	1
2992	Ethylbenzene	0.7	0	0			0	0
2946	Ethylene dibromide	0.00005	0	0			0	0
2034	Glyphosate	0.7	0	0			1	1
2065	Heptachlor	0.0004	0	0			1	1
2067	Heptachlor epoxide	0.0002	0	0			1	1
2274	Hexachlorobenzene	0.001	0	0			1	1
2042	Hexachlorocyclo-pentadiene	0.05	0	0			1	1
2010	Lindane	0.0002	0	0			1	1
2015	Methoxychlor	0.04	0	0			1	1
2989	Monochlorobenzene	0.1	0	0			1	1
2968	o-Dichlorobenzene	0.6	0	0			0	0

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
2969	para-Dichlorobenzene	0.075	0	0			0	0
2383	Total polychlorinated biphenyls (PCB's)	0.0005	0	0			1	1
2326	Pentachlorophenol	0.001	0	0			1	1
2987	Tetrachloroethylene	0.005	0	0			0	0
2984	Trichloroethene	0.005	0	0			0	0
2996	Styrene	0.1	0	0			0	0
2991	Toluene	1.0	0	0			0	0
2979	trans-1,2-Dichloroethylene	0.1	0	0			0	0
2955	Xylenes (total)	10	0	0			0	0
2020	Toxaphene	0.003	0	0			1	1
2036	Oxamyl (Vydate)	0.2	0	0			1	1
2040	Picloram	0.5	0	0			1	1

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
2037	Simazine	0.004	0	0			1	1
2976	Vinyl chloride	0.002	0	0			0	0
	<u>Subtotal</u>		0	0			1 (see notes #2)	1
	<u>Stage 1 Disinfectant Byproducts Rule</u>							
1009	Chlorite	1.0	0	0			0	0
1011	Bromate	0.010	0	0			0	0
1006	Chloramines	4.0	0	0			0	0
1008	Chlorine Dioxide	0.8	0	0			0	0
0999	Chlorine	4.0	0	0			0	0
2950	Total Trihalomethanes (Section 7.0 systems)	0.08	3	2			0	0
2456	Total Haloacetic Acids	0.06	0	0			0	0

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
2920	Total Organic Carbon Removal Ratio	1.0			0	0	0	0
	<u>Subtotal</u>		3	2	0	0	0	0
	<u>Inorganic Contaminants</u>							
1074	Antimony	0.006	0	0			0	0
1005	Arsenic	0.05	0	0			0	0
1094	Asbestos (>10 micrometers)	7 million fibers/L	0	0			5	5
1010	Barium	2.0	0	0			0	0
1075	Beryllium	0.004	0	0			0	0
1015	Cadmium	0.005	0	0			0	0
1020	Chromium	0.1	0	0			0	0
1024	Cyanide (as free cyanide)	0.2	0	0			0	0

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
1025	Fluoride	4.0	0	0			0	0
1035	Mercury	0.002	0	0			0	0
1040	Nitrate	10	1	1			6	6
1041	Nitrite	1	0	0			7	7
1045	Selenium	0.05	0	0			0	0
SM	Sodium						0	0
1085	Thallium	0.002	0	0			0	0
1038	Total nitrate and nitrite	10 (as Nitrogen)	0	0			0	0
	<u>Subtotal</u>		1	1			18	18
	<u>Radionuclide MCLs</u>							
4000	Gross alpha	15 pCi/l	0	0			0	0
4010	Radium-226 and radium-228	5 pCi/l	0	0			0	0
4101	Gross beta	4 mrem/yr	0	0			0	0

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
	<b><u>Subtotal</u></b>		0	0			0	0
	<b><u>Total Coliform Rule</u></b>							
21	Acute MCL violation	Presence	2	2				
22	Non-acute MCL violation	Presence	50	38				
23,25	Major routine Major repeat						33	26
24,26	Minor routine Minor repeat						7	6
34	Groundwater Rule						11	11
75	Public Education						2	2
	<b><u>Subtotal</u></b>		52	40			53	45
	<b><u>Surface Water Treatment Rule</u></b>							

**State:** Rhode Island

**Reporting Interval:** January 1, 2012 through  
December 31, 2012

SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
36	Monitoring, routine/repeat						0	0
41, 43, 44	Treatment techniques				1	1		
	Unfiltered Systems							
31	Monitoring, routine/repeat						1	1
42	Failure to filter				0	0		
	<u>Subtotal</u>				1	1	1	1
	<u>Lead and Copper Rule</u>							
51	Initial lead and copper tap M/R		0	0			1	1
52,56	Follow-up or routine lead and copper tap M/R		0	0			15	10
53	Water Quality Parameters						2	2
57	OCCT/SOWT RECOM./STUDY						0	0

<b>State:</b> Rhode Island <b>Reporting Interval:</b> January 1, 2012 through December 31, 2012								
SDWIS Codes		MCL (mg/l)	MCLs		Treatment Techniques		Significant Monitoring/Reporting	
			Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations	Number of Violations	Number of Systems With Violations
58,62	Treatment Installation				0	0		
65	Public education						1	1
	<u>Subtotal</u>		0	0	0	0	19	14
	<u>Consumer Confidence Reports (CCR)</u>							
71	CCR Complete failure to report (Major)						0	0
72	CCR Continent Inadequacy (Minor)						1	1
	<u>Subtotal</u>						1	1
<u>Totals</u>			54	41	1	1	88	78

Notes:

- 1) Values are in milligrams per liter (mg/l), unless otherwise specified.
- 2) Monitoring violations for Volatile Organic Compounds are issued as a single violation, not as violations for each of the 21 regulated contaminants.



### **Definitions for Appendix (Compliance Table)**

The following definitions apply to Appendix A (Compliance Table) above.

**Filtered Systems:** Water systems that have installed filtration treatment [40 CFR 141, Subpart H].

**Inorganic Contaminants:** Non-carbon-based compounds such as metals, nitrates, and asbestos. These contaminants are naturally-occurring in some water, but can get into water through farming, chemical manufacturing, and other human activities. EPA has established MCLs for 15 inorganic contaminants [40 CFR 141.62].

**Lead and Copper Rule:** This rule established national limits on lead and copper in drinking water [40 CFR 141.80-91]. Lead and copper corrosion pose various health risks when ingested at any level, and can enter drinking water from household pipes and plumbing fixtures. States report violations of the Lead and Copper Rule in the following six categories:

*Initial lead and copper tap M/R:* SDWIS Violation Code 51 indicates that a system did not meet initial lead and copper testing requirements, or failed to report the results of those tests to the State.

*Follow-up or routine lead and copper tap M/R:* SDWIS Violation Code 52 indicates that a system did not meet follow-up or routine lead and copper tap testing requirements, or failed to report the results.

*Treatment installation:* SDWIS Violation Codes 58 AND 62 indicate a failure to install optimal corrosion control treatment system (58) or source water treatment system (62) which would reduce lead and copper levels in water at the tap. [One number is to be reported for the sum of violations in these two categories].

*Public education:* SDWIS Violation Code 65 shows that a system did not provide required public education about reducing or avoiding lead intake from water.

**Maximum Contaminant Level (MCL):** The highest amount of a contaminant that EPA allows in drinking water. MCLs ensure that drinking water does not pose either a short-term or long-term health risk. MCLs are defined in milligrams per liter (parts per million) unless otherwise specified.

**Monitoring:** EPA specifies which water testing methods the water systems must use, and sets schedules for the frequency of testing. A water system that does not follow EPA's schedule or methodology is in violation [40 CFR 141].

States must report monitoring violations that are significant as determined by the EPA Administrator and in consultation with the States. For purposes of this report, significant monitoring violations are major violations and they occur when no samples are taken or no results are reported during a compliance period. A major monitoring violation for the surface water treatment rule occurs when at least 90% of the required samples are not taken or results are not reported during the compliance period.

**Organic Contaminants:** Carbon-based compounds, such as industrial solvents and pesticides. These contaminants generally get into water through runoff from cropland or discharge from factories. EPA has set legal limits on 54 organic contaminants that are to be reported [40 CFR 141.61].

**Radionuclides:** Radioactive particles which can occur naturally in water or result from human activity. EPA has set legal limits on four types of radionuclides: radium-226, radium-228, gross alpha, and beta particle/photon radioactivity [40 CFR 141]. Violations for these contaminants are to be reported using the following three categories:

*Gross alpha:* SDWIS Contaminant Code 4000 for alpha radiation above MCL of 15 picocuries/liter. Gross alpha includes radium-226 but excludes radon and uranium.

*Combined radium-226 and radium-228:* SDWIS Contaminant Code 4010 for combined radiation from these two isotopes above MCL of 5 pCi/L.

*Gross beta:* SDWIS Contaminant Code 4101 for beta particle and photon radioactivity from man-made radionuclides above 4 millirem/year.

**Reporting Interval:** The reporting interval for violations to be included in the PWS Annual Compliance Report, which is to be submitted to EPA by July 1, 2010, is from January 1, 2010 through December 31, 2010.

**SDWIS Code:** Specific numeric codes from the Safe Drinking Water Information System (SDWIS) have been assigned to each violation type included in this report. The violations to be reported include exceeding contaminant MCLs, failure to comply with treatment requirements, and failure to meet monitoring and reporting requirements. Four-digit SDWIS Contaminant Codes have also been included in the chart for specific MCL contaminants.

**SM:** State monitoring requirement for contaminants not regulated under the Safe Drinking Water Act (Sodium)

**Surface Water Treatment Rule:** The Surface Water Treatment Rule establishes criteria under which water systems supplied by surface water sources, or ground water sources under the direct influence of surface water, must filter and disinfect their water [40 CFR 141, Subpart H]. Violations of the “Surface Water Treatment Rule” are to be reported for the following four categories:

*Monitoring, routine/repeat (for filtered systems):* SDWIS Violation Code 36 indicates a system’s failure to carry out required tests, or to report the results of those tests.

*Treatment techniques (for filtered systems):* SDWIS Violation Code 41 shows a system’s failure to properly treat its water.

*Monitoring, routine/repeat (for unfiltered systems):* SDWIS Violation Code 31 indicates a system’s failure to carry out required water tests, or to report the results of those tests.

*Failure to filter (for unfiltered systems):* SDWIS Violation Code 42 shows a system’s failure to properly treat its water. EPA will supply data for this violation code to the States.

**Total Coliform Rule (TCR):** The Total Coliform Rule establishes regulations for microbiological contaminants in drinking water. These contaminants can cause short-term health problems. If no samples are collected during the one-month compliance period, a significant monitoring violation occurs. States are to report four categories of violations:

*Acute MCL violation:* SDWIS Violation Code 21 indicates that the system found fecal coliform or E. coli, potentially harmful bacteria, in its water, thereby violating the rule.

*Non-acute MCL violation:* SDWIS Violation Code 22 indicates that the system found total coliform in samples of its water at a frequency or at a level that violates the rule. For systems collecting fewer than 40 samples per month, more than one positive sample for total coliform is a violation. For systems collecting 40 or more samples per month, more than 5% of the samples positive for total coliform is a violation.

*Major routine and repeat monitoring:* SDWIS Violation Codes 23 and 25 show that a system did not perform any monitoring. (One number is to be reported for the sum of violations in these two categories.)

*Minor routine and repeat monitoring:* SDWIS Violation Codes 24 and 26 show that a system did not did not comply with the required monitoring schedule, by failing to collect the required number of samples. . (One number is to be reported for the sum of violations in these two categories.)

**Treatment Techniques:** A water disinfection process that EPA requires instead of an MCL for contaminants that laboratories cannot adequately measure. Failure to meet other operational and system requirements under the Surface Water Treatment and the Lead and Copper Rules have also been included in this category of violation for purposes of this report.

**Unfiltered Systems:** Water systems that do not need to filter their water before disinfecting it because the source is very clean [40 CFR, Subpart H].

**Violation:** A failure to meet any state or federal drinking water regulation.

STATE OF RHODE ISLAND AND PROVIDENCE PLANTATIONS

THE HONORABLE  
LINCOLN D. CHAFEE, GOVERNOR



MICHAEL FINE, M.D.  
DIRECTOR  
DEPARTMENT OF HEALTH

JUNE A. SWALLOW, P.E.  
CHIEF  
OFFICE OF DRINKING WATER QUALITY

# 1<sup>st</sup> Quarter FY 2013 GPRA Results

## RI

	GPRA-sys	GPRA-pop
'13 National Target	90%	92%
'13 Actual Region I	86.3%	94.0%
'13 RI	90.0%	90.2%

**Measure:** *Percent of person months (i.e., all persons served times 12 months) during which community water systems provide drinking water that meets all applicable health-based standards*

**Explanation:** This measure tracks the duration of a population's exposure to violations. For example, some systems may receive a violation for an incident that lasts one day (e.g., turbidity increase due to storm event) as opposed to a longer term event.

These statistics are calculated each quarter using the most recent 4 quarters of health-based compliance information in SDWISFED for community systems.

# 1<sup>st</sup> Quarter FY 2013 GPRA Results

## RI

	% Person Months
'13 Target National	95.0%
'13 Actual National	95.6%
'13 Actual Region 1	97.4%
'13 Actual RI	94.9%

**% Person months** is the % of community water that provide drinking water that meets all applicable health based standards.

These statistics are calculated each quarter using the most recent 4 quarters of health-based compliance information in SDWISFED for community systems.

# 1<sup>st</sup> Quarter FY 2013 GPRA Results

## Top Ten (actually 9)

Largest CWSs with Reported Health-Based Violations in 13q1.

PWS ID	PWS Name	Status	P Source	Ret Pop Srvd	C Code	C Type	C Name	V Code	V Type	V Name
RI1592010	NEWPORT-CITY OF	Active	SW	43809	2950	St1_DBP	TTHM	2	MCL	MCL, Average
RI1559512	WESTERLY WATER DEPARTMENT	Active	GW	38000	3100	TCR	Coliform (TCR)	22	MCL	MCL, Monthly (TCR)
RI1000016	NAVAL STATION, NEWPORT	Active	SWP	7871	2950 (2)	St1_DBP (2)	TTHM (2)	2 (2)	MCL (2)	MCL, Average (2)
RI1615623	SOUTH KINGSTOWN-SOUTH SHORE	Active	GW	3811	3100	TCR	Coliform (TCR)	22	MCL	MCL, Monthly (TCR)
RI1592020	PASCOAG UTILITY DISTRICT, WATER DIVISION	Active	GW	3500	3100	TCR	Coliform (TCR)	22	MCL	MCL, Monthly (TCR)
RI1592023	PRUDENCE ISLAND WATER DISTRICT	Active	GW	1000	5000	LCR	Lead & Copper Rule	85	TT	Public Education
RI1647512	CENTRAL BEACH FIRE DISTRICT	Active	GW	470	5000	LCR	Lead & Copper Rule	59	TT	WQP Entry Point Non-Compliance
RI1559513	SHADY HARBOR FIRE DISTRICT	Active	GW	162	3100	TCR	Coliform (TCR)	22	MCL	MCL, Monthly (TCR)
RI1900053	CANONCHET CLIFFS WATER ASSOCIATION INC.	Active	GW	154	3100 (2)	TCR (2)	Coliform (TCR) (2)	22 (1), 21 (1)	MCL (2)	MCL, Monthly (TCR) (1), MCL, Acute (TCR) (1)



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Providence, RI 02908

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Boyce Spinelli  
*General Manager*

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May 14, 2013

June Swallow, PE  
Chief, Drinking Water Quality  
R.I. Department of Health  
Cannon Building, Room 209  
Three Capitol Hill  
Providence, R.I. 02908-5097

RE: pH Transition Implementation Plan  
Philip J. Holton Water Purification Plant  
April 2013 Monthly Report  
PWSID 1592024

Dear Ms. Swallow:

Providence Water is pleased to submit the attached April 2013 Monthly Report. The format of the Monthly Report continues to follow the outline of RIDOH's December 6, 2012 letter. Providence Water continues to work closely with certain members of the Expert Panel.

The commencement of the Unidirectional Flushing (UDF) Program is still slated for mid-May. Under the Water Main Replacement Program, two new contracts recently had bid openings. The bids were evaluated, and three contractors will be awarded contracts for the 2013 construction season, extending into 2014.

Should you have any questions, please feel free to contact me at 521-6300, Ext. 7291 or [ggiasson@provwater.com](mailto:ggiasson@provwater.com).

Respectfully,  
PROVIDENCE WATER SUPPLY BOARD

Gregg Giasson, PE  
Senior Director of Operations

Attachment: April 2013 Monthly Report

cc: Clay Commons	Peter LePage	Steve Soito, PE
Boyce Spinelli	Steve Santaniello	Fred Crosby
Joseph Sprenulli	Rich Razza	Mike Covellone
Ricky Caruolo	Paul Gadoury, PE	John Phillips, PE





**pH Transition Implementation Plan  
Philip J. Holton Water Purification Plant  
Monthly Report  
April 2013**

This Monthly Report follows the outline of the RIDOH December 6, 2012 letter requesting monthly updates on all activity related to corrosion control.

**1. pH Transition**

The initial transition to a higher pH began on Wednesday, February 6, 2013.

The second and final transition to the higher pH of 10.2 began on Monday, March 25, 2013 and the CO<sub>2</sub> dose was terminated.

During April, the Treatment Plant Effluent and Academy Avenue pH and Alkalinity had the following values:

		Effluent Water		Academy Avenue	
		<u>pH (SU)</u>	<u>T. Alkalinity (mg/l)</u>	<u>pH (SU)</u>	<u>T. Alkalinity (mg/l)</u>
Min.	10.28	15.10	10.13	13.80	
Max.	10.51	17.50	10.40	16.20	
Avg.	10.41	16.33	10.27	14.97	

See Attachment No. 1 - April pH and Alkalinity Data Tables.

## **2. Special Sampling Studies of Lead Service Line**

### **A. Sequential and LSL Sampling & Testing**

The Post-CCTC sampling began on February 11, and continues based on the approved Protocol.

Sampling data received to date extends through the first week of April, with the next round of sampling to take place in the first week of May. The data received so far suggests a very modest decrease in total lead, particularly in the samples of water that had been stagnant in the lead service line at most locations.

See Attachment No. 2 - Samples from Lead Service Line, for the eight participant site/address test results, for essentially all metals.

### **B. PRS Stations' Monitoring (Academy Ave., Brown University, Commercial Building)**

The PRS Stations sampling and testing that was resumed at the end of January continues.

### **C. Virginia Tech (VT) Pipe Loop Rigs (Academy Ave., Water Treatment Plant)**

Sampling and testing continues on the VT Rigs that were placed back in service the last week in February. The intention continues to sample and test once per month.

## **3. Special Sampling Studies - Lead attached to Iron Particles**

Marc Edwards, with his associate Sheldon Masters (both from Virginia Tech), continue to study the relationship between elevated iron concentrations and lead release, and will share any new findings.

#### **4. Special Sampling Studies - TCR Sites, LCR Sites, WTP Finished Water**

##### **A. Special Total Coliform Rule (TCR) Sites (4)**

Four TCR sites were chosen for ease of sampling and their dispersed geographical locations. The additional sampling and testing that began at these sites on February 1, continues once every two weeks.

##### **B. Lead and Copper Rule (LCR) Sites**

The additional testing of the LCR sites (100) during the normal 6 month semesters that began in December 2012, continues. The additional tests being conducted, as requested by the Expert Panel, are for Dissolved Lead, Total Iron, and Total Zinc.

##### **C. Total Coliform Rule (TCR) Sites (44)**

The added Turbidity testing continues.

##### **D. WTP Finished Water Sampling**

The addition of Oxygen Reduction Potential (ORP) to the typical daily analyses of the finished water, continues with weekly field tests and laboratory tests every 8 weeks Post-CCTC.

#### **5. Experimental Pipe Loops**

The eight, four (4) foot lead service lines (5/8" inch) that were harvested for use in the pipe loop racks have been cut into sixteen, two (2) foot samples, ready for future insertion into the pipe loops. They will initially be conditioned by hand using the manual fill and dump method. This fill and dump method will be employed while the pipe loop racks are being fabricated, and then the best eight will be inserted into the loops for further conditioning.

A more detailed schematic was developed with all components identified such as rotometers, throttling and ball valves, sampling ports, etc. and then modified to include the free discharge of the effluent and a single discharge manifold stack. The frame work of the loop support system was designed and the PO accounts set up with the suppliers.

As per the Expert Panel's report, further consultation with the Panel is warranted once the current data is analyzed to determine what future experiments/pilot studies may be warranted.

# April

Date	Effluent Water		Academy Ave., Tap	
	pH SU	T. Alk. mg/l	pH SU	T. Alk. mg/l
4/1/2013	10.47	17.00	10.32	15.20
4/2/2013	10.48	17.00	10.28	15.00
4/3/2013	10.51	17.50	10.34	16.00
4/4/2013	10.38	16.70	10.36	15.50
4/5/2013	10.45	17.00	10.32	15.70
4/6/2013	10.45	17.20		
4/7/2013				
4/8/2013	10.50	17.20	10.40	16.20
4/9/2013	10.45	17.10	10.20	15.00
4/10/2013	10.39	16.50		
4/11/2013	10.40	16.10	10.28	14.80
4/12/2013	10.31	15.70	10.28	15.00
4/13/2013	10.45	15.80		
4/14/2013				
4/15/2013	10.43	16.20	10.31	15.10
4/16/2013	10.45	16.80	10.32	15.20
4/17/2013	10.49	17.00	10.28	15.00
4/18/2013	10.50	17.00	10.31	15.50
4/19/2013	10.41	16.10	10.27	15.00
4/20/2013	10.34	15.80		
4/21/2013				
4/22/2013	10.36	16.10	10.23	14.70
4/23/2013	10.37	16.10	10.24	14.60
4/24/2013	10.39	15.50	10.20	14.70
4/25/2013	10.39	15.80	10.22	14.20
4/26/2013	10.34	15.50	10.15	14.30
4/27/2013	10.36	15.60		
4/28/2013				
4/29/2013	10.28	15.10	10.13	13.80
4/30/2013	10.34	15.20	10.18	13.80
Minimum	10.28	15.10	10.13	13.80
Maximum	10.51	17.50	10.40	16.20
Average	10.41	16.33	10.27	14.97

# Loc #1, 57 Holburn Ave

Date: 1/4/13; inside faucet E301238

Flow rate = 1.49 gpm pH = 9.33 / 9.53

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0052	0.0010	0.0010	0.20	0.051	0.0520	0.0100	0.0051	0.0048
2 #02, 1/2 Liter	0.0028	0.0010	0.0010	0.19	0.051	0.0430	0.0110	0.0051	0.0038
3 #03, 1 Liter	0.0010	0.0010	0.0010	0.22	0.051	0.0110	0.0026	0.0051	0.0071
4 #04, 1 Liter	0.0010	0.0010	0.0010	0.23	0.051	0.0110	0.0021	0.0051	0.0062
5 #05, 1 Liter	0.0012	0.0010	0.0010	0.22	0.051	0.0082	0.0023	0.0051	0.0051
6 #06, 1 Liter	0.0012	0.0010	0.0010	0.23	0.051	0.0078	0.0021	0.0051	0.0040
7 #07, 3 min 1 Liter	0.0010	0.0010	0.0010	0.22	0.051	0.0120	0.0025	0.0051	0.0072

Date: 1/18/13; outside spigot E301D07

Flow rate = 1.69 gpm pH = 9.61 / 9.90

temp = 18.9 / 7.6

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	1.3000	0.0440	0.43	0.065	0.4100	0.0480	0.056	0.0150	0.6000
2 #02, 1/2 Liter	0.0045	0.0010	0.21	0.051	0.0160	0.0031	0.0051	0.0042	0.0095
3 #03, 1 Liter	0.0100	0.0010	0.20	0.051	0.0093	0.0026	0.0051	0.0040	0.0250
4 #04, 1 Liter	0.0260	0.0019	0.21	0.051	0.0076	0.0019	0.0051	0.0047	0.0280
5 #05, 1 Liter	0.0190	0.0013	0.21	0.051	0.0044	0.0016	0.0051	0.0050	0.0290
6 #06, 1 Liter	0.0180	0.0045	0.22	0.067	0.0032	0.0015	0.0051	0.0058	0.0250
7 #07, 1 Liter	0.0042	0.0010	0.24	0.083	0.0026	0.0015	0.0051	0.0075	0.0190
8 #08, 3 min 1 Liter	0.0010	0.0010	0.24	0.064	0.0010	0.0010	0.0051	0.0076	0.0210





# Date: 2/20/13; outside spigot E302E21

Flow rate = 2.22 gpm									
pH = 9.77 / 9.94									
temp = 15.4 / 8.0									
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc	
1 #01, 1/2 Liter	0.0095	0.0010	0.2500	0.0510	0.0250	0.0027	0.0051	0.0058	0.0053
2 #02, 1 Liter	0.0120	0.0010	0.2500	0.0510	0.0027	0.0010	0.0051	0.0062	0.0120
3 #03, 3 min 1 Liter	0.0010	0.0010	0.2500	0.0510	0.0010	0.0010	0.0051	0.0072	0.0092

# Date: 2/21/13; inside faucet E302E20

ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc	
1 #01, 1/2 Liter	0.0210	0.0011	0.3100	0.0510	0.0270	0.0056	0.0051	0.0083	0.0550
2 #02, 1 Liter	0.0081	0.0010	0.1800	0.0510	0.0035	0.0012	0.0051	0.0061	0.0250
3 #03, 3 min 1 Liter	0.0045	0.0010	0.2000	0.0510	0.0013	0.0010	0.0051	0.0077	0.0140

# Date: 3/1/13; inside faucet E303079

ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc	
1	0.0030	0.0010	0.2400	0.0510	0.0200	0.0080	0.0051	0.0047	0.0680
2	0.0027	0.0010	0.2400	0.0510	0.0075	0.0031	0.0051	0.0051	0.0140
3	0.0010	0.0010	0.2500	0.0580	0.0010	0.0010	0.0051	0.0070	0.0110

# Date: 3/6/13; outside faucet E303572

ATP = 646 ME/mL									
Flow rate = 2.24 gpm									
pH = 9.83 / 9.94									
temp = 17 / 8.5									
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc	
1	0.0150	0.0010	0.4100	0.0510	0.0140	0.0067	0.0051	0.0069	0.0056
2	0.0170	0.0018	0.4000	0.0720	0.0052	0.0015	0.0051	0.0094	0.0120
3	0.0010	0.0010	0.3100	0.0510	0.0010	0.0010	0.0051	0.0094	0.0110



**Date: 3/7/13; inside faucet**

**E303571**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0052	0.0010	0.2300	0.0510	0.0340	0.0120	0.0051	0.0049	0.0140
2	0.0053	0.0010	0.1800	0.0510	0.0016	0.0010	0.0051	0.0049	0.0150
3	0.0010	0.0010	0.2100	0.0510	0.0018	0.0010	0.0051	0.0070	0.0140

**Date: 4/2/13; inside faucet**

**E304162**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0035	0.0010	0.1200	0.0510	0.0140	0.0057		0.0026	0.0051
2	0.0092	0.0010	0.1300	0.0510	0.0010	0.0010		0.0032	0.0110
3	0.0010	0.0010	0.1400	0.0510	0.0010	0.0010		0.0040	0.0110

# Date: 4/9/13; outside faucet

E304758

ATP = 1542		Flow rate = 2.17 gpm		pH = 10.0 / 10.11		temp = 13.4 / 10.0	
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Manganese	Zinc
0.0110	0.0010	0.1600	0.0510	0.0090	0.0026	0.0037	0.0072
0.0370	0.0016	0.1700	0.0510	0.0054	0.0016	0.0038	0.0120
0.0013	0.0010	0.1800	0.0510	0.0010	0.0010	0.0048	0.0093



Flow rate = 1.57 gpm

$$\text{pH} = 9.60 / 9.69$$
[illegible]

## Sample date 1/23/2013; Outside spigot; F301G29

Flow rate = 1.46 gpm

pH = 9.70 / 9.81

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0089	0.0010	<b>0.120</b>	0.051	<b>0.0280</b>	<b>0.0048</b>	0.0051	<b>0.0023</b>	<b>0.0860</b>
2	#02, 1/2 Liter	0.0120	0.0032	0.092	0.051	<b>0.0210</b>	<b>0.0054</b>	0.0051	0.0020	<b>0.0410</b>
3	#03, 1 Liter	0.0170	<b>0.0050</b>	<b>0.098</b>	0.051	0.0051	0.0011	0.0051	<b>0.0021</b>	0.0320
4	#04, 1 Liter	<b>0.0180</b>	0.0020	0.090	0.051	0.0021	0.0015	0.0051	0.0020	0.0051
5	#05, 1 Liter	<b>0.0200</b>	<b>0.0070</b>	0.091	0.051	0.0010	0.0010	0.0051	0.0020	0.0051
6	#06, 1 Liter	0.0068	0.0015	0.095	0.051	0.0010	0.0010	0.0051	0.0023	0.0051
7	#07, 3 min 1 Liter	0.0012	0.0010	<b>0.098</b>	0.051	0.0010	0.0010	0.0051	0.0026	0.0051

Sample date 1/30/2013; Outside spigot; E301K65

Flow rate = 1.59 gpm

pH = 9.66 / 9.73

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0090	0.0010	<b>0.1100</b>	0.0510	<b>0.0160</b>	<b>0.0074</b>	0.0051	0.0020
2	#02, 1 Liter	0.0330	<b>0.0110</b>	0.0970	0.0510	<b>0.0072</b>	<b>0.0039</b>	0.0051	<b>0.0750</b>
3	#03, 1 Liter	0.0430	<b>0.0110</b>	0.0940	0.0510	0.0014	0.0014	0.0051	0.0150
4	#04, 1 Liter	<b>0.0450</b>	0.0100	0.0950	0.0510	0.0016	0.0017	0.0051	<b>0.0180</b>
5	#05, 1 Liter	<b>0.0460</b>	0.0100	0.0940	0.0510	0.0010	0.0018	0.0051	0.0140
6	#06, 1 Liter	0.0098	0.0028	<b>0.1100</b>	0.0510	0.0010	0.0012	0.0051	0.0110
7	#07, 3 min 1 Liter	0.0012	0.0010	<b>0.1100</b>	0.0510	0.0010	0.0010	<b>0.0033</b>	<b>0.0033</b>

## Sample date 2/12/2013; Inside spigot; E302848

Flow rate = 1.77 gpm

pH = 9.48 / 9.56

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.005	0.001	0.11	0.051	0.0092	0.0046	0.0051	0.0025	0.027
2 #02, 1 Liter	0.027	0.0058	0.07	0.051	0.001	0.001	0.0051	0.002	0.011
3 #03, 3 min 1 Liter	0.001	0.001	0.11	0.058	0.001	0.001	0.0051	0.0031	0.009
4 #04, 3 min 1 Liter	0.001	0.001	0.11	0.051	0.001	0.001	0.0051	0.0033	0.0051

## Sample date 2/13/2013; Outside spigot; E302952

Flow rate = 1.70 gpm

$$pH = 9.56 / 9.66$$

temp = 12.7 / 7.7

	ppm	Diss Lead	Iron ppm	Copper ppm	pH	Tin ppm	Manganese ppm	Zinc ppm
1 #01, 1/2 Liter	0.062	0.0024	0.19	0.051	0.02	0.0075	0.0051	0.0053
2 #02, 1 Liter	0.031	0.0053	0.086	0.051	0.001	0.001	0.0051	0.0091
3 #03, 3 min 1 Liter	0.001	0.001	0.089	0.051	0.001	0.0012	0.0051	0.0086
4 #04, 3 min 1 Liter	0.001	0.001	0.089	0.051	0.001	0.001	0.0051	0.0085

**Sample date 2/21/2013; Outside spigot; E302E17**

Flow rate = 2.30 gpm

pH = 9.93 / 10.02

temp = 10.2 / 8.2

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0120	0.0010	0.0920	0.0510	0.0140	0.0061	0.0051	0.0020	0.0120
2 #02, 1 Liter	0.0270	0.0010	0.0980	0.0510	0.0012	0.0010	0.0051	0.0022	0.0140
3 #03, 3 min 1 Liter	0.0010	0.0010	0.1400	0.0510	0.0010	0.0010	0.0051	0.0040	0.0110
4 #04, 3 min 1 Liter	0.0010	0.0010	0.1300	0.0510	0.0010	0.0010	0.0051	0.0039	0.0087

**Sample date 2/20/2013; Inside spigot; E302D40**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0110	0.0010	0.1500	0.0510	0.0011	0.0010	0.0051	0.0039	0.0051
2 #02, 1 Liter	0.0130	0.0017	0.1500	0.0510	0.0010	0.0010	0.0051	0.0040	0.0120
3 #03, 3 min 1 Liter	0.0022	0.0010	0.1600	0.0510	0.0010	0.0010	0.0051	0.0043	0.0110
4 #04, 3 min 1 Liter	0.0014	0.0010	0.1600	0.0510	0.0010	0.0010	0.0051	0.0041	0.0120

**Sample date 2/26/2013; Inside spigot; E302H07**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0018	0.001	0.14	0.051	0.001	0.001	0.0051	0.0036	0.0051
2	0.0014	0.001	0.14	0.051	0.001	0.001	0.0051	0.0037	0.0099
3	0.0013	0.001	0.14	0.051	0.001	0.001	0.0051	0.0039	0.0095
4	0.0011	0.001	0.15	0.051	0.001	0.001	0.0051	0.0037	0.0099

**Sample date 2/27/2013; Outside spigot; E302159**

ATP = 104 ME/mL

Flow rate = 1.93 gpm

pH = 9.78 / 9.96

temp = 13.4 / 9.6

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0049	0.0010	0.0790	0.0510	0.0160	0.0069	0.0051	0.0020	0.0092
2	0.0290	0.0042	0.0760	0.0510	0.0011	0.0010	0.0051	0.0020	0.0097
3	0.0010	0.0010	0.0880	0.0510	0.0010	0.0010	0.0051	0.0023	0.0120
4	0.0010	0.0010	0.0880	0.0510	0.0010	0.0010	0.0051	0.0022	0.0088

**Sample date 3/5/2013; Inside spigot; E303294**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0260	0.0064	0.0640	0.0510	0.0013	0.0011	0.0051	0.0020	0.0051
2	0.0014	0.0010	0.1200	0.0510	0.0010	0.0010	0.0051	0.0032	0.0090
3	0.0012	0.0010	0.1300	0.0510	0.0010	0.0010	0.0051	0.0034	0.0098
4	0.0011	0.0010	0.1300	0.0510	0.0010	0.0010	0.0051	0.0034	0.0100

**Sample date 3/6/2013; Outside spigot; E303574**

ATP = 427 ME/mL

Flow rate = 2.04 gpm

pH = 9.77 / 9.86

temp = 13.6 / 10.5

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0076	0.0016	0.0610	0.0510	0.0120	0.0069	0.0051	0.0020	0.0100
2	0.0270	0.0079	0.0570	0.0510	0.0011	0.0010	0.0051	0.0020	0.0110
3	0.0011	0.0010	0.0730	0.0510	0.0010	0.0010	0.0051	0.0020	0.0099
4	0.0012	0.0010	0.0710	0.0510	0.0010	0.0010	0.0051	0.0020	0.0250

Sample date 4/2/2013; Inside spigot; E304160

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0032	0.001	0.088	0.051	0.001	0.001	0.001	0.002	0.0051
2	0.0015	0.001	0.086	0.051	0.001	0.001	0.001	0.002	0.011
3	0.0014	0.001	0.089	0.051	0.001	0.001	0.001	0.0023	0.011

Sample date 4/9/2013; Outside spigot;

ATP = 3268 ME/ml

E304A24

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0130	0.0010	0.0940	0.0510	0.0150	0.0061	0.0027	0.0240	
2	0.0220	0.0092	0.0530	0.0510	0.0057	0.0040	0.0020	0.0160	
3	0.0016	0.0010	0.0540	0.0510	0.0010	0.0010	0.0020	0.0110	

Flow rate = 2.08 gpm pH = 9.76 / 9.85 temp = 18.3 / 17.2



# Loc #3, 32 Lorimer Ave

Date: 1/10/13; outside spigot E301770

Flow rate = 2.04 gpm

pH = 9.50 / 9.63

Units	Parameter	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
		Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc											
1	#01, 1/2 Liter	Result	0.0140	0.0050	0.051	0.051	0.0160	0.0060	0.0051	0.1300											
2	#02, 1/2 Liter	Result	0.0230	0.0014	0.220	0.051	0.0100	0.0071	0.0051	0.2000											
3	#03, 1 Liter	Result	0.0240	0.0042	0.200	0.051	0.0360	0.0120	0.0051	0.0280											
4	#04, 1 Liter	Result	0.0850	0.0100	0.210	0.051	0.0064	0.0027	0.0051	0.0230											
5	#05, 1 Liter	Result	0.0870	0.0100	0.210	0.051	0.0019	0.0014	0.0051	0.0220											
6	#06, 1 Liter	Result	0.0470	0.0052	0.190	0.051	0.0018	0.0012	0.0051	0.0220											
7	#07, 1 Liter	Result	0.0049	0.0010	0.058	0.051	0.0012	0.0010	0.0051	0.0220											
8	#08, 3 min 1 Liter	Result	0.0023	0.0010	0.053	0.051	0.0010	0.0010	0.0051	0.0210											

Date: 1/11/13; outside spigot E301806

Flow rate = 2.03 gpm

pH = 9.50 / 9.56

Units	Parameter	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
		Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc											
1	#01, 1/2 Liter	Result	0.0160	0.0054	0.051	0.051	0.0120	0.0080	0.0051	0.0020	0.1100										
2	#02, 1/2 Liter	Result	0.0120	0.0020	0.052	0.051	0.0120	0.0068	0.0051	0.0020	0.1000										
3	#03, 1 Liter	Result	0.0210	0.0099	0.051	0.051	0.0250	0.0140	0.0051	0.0020	0.0280										
4	#04, 1 Liter	Result	0.0520	0.0230	0.053	0.051	0.0041	0.0032	0.0051	0.0020	0.0220										
5	#05, 1 Liter	Result	0.0500	0.0210	0.051	0.051	0.0018	0.0016	0.0051	0.0020	0.0250										
6	#06, 1 Liter	Result	0.0220	0.0025	0.150	0.051	0.0017	0.0012	0.0051	0.0042	0.0230										
7	#07, 1 Liter	Result	0.0040	0.0010	0.150	0.051	0.0012	0.0010	0.0051	0.0048	0.0190										
8	#08, 3 min 1 Liter	Result	0.0025	0.0010	0.140	0.051	0.0010	0.0010	0.0051	0.0049	0.0230										

**Date: 1/14/13; inside faucet****E301A06**

Flow rate = 1.75 gpm

pH = 9.17 / 9.31

Units	Parameter	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
		Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc								
1	#01, 1/2 Liter	Result	0.0120	0.0036	0.074	0.051	0.0450	0.0240	0.0051	0.0026								
2	#02, 1/2 Liter	Result	0.0170	0.0012	0.088	0.051	0.0320	0.0140	0.0051	0.0026								
3	#03, 1 Liter	Result	0.0180	0.0054	0.084	0.051	0.0300	0.0150	0.0051	0.0022								
4	#04, 1 Liter	Result	0.0370	0.0130	0.076	0.051	0.0190	0.0095	0.0051	0.0020								
5	#05, 1 Liter	Result	0.0700	0.0240	0.082	0.051	0.0042	0.0026	0.0051	0.0021								
6	#06, 1 Liter	Result	0.0640	0.0180	0.074	0.051	0.0028	0.0018	0.0051	0.0020								
7	#07, 1 Liter	Result	0.0140	0.0042	0.054	0.051	0.0023	0.0018	0.0051	0.0024								
8	#08, 3 min 1 Liter	Result	0.0026	0.0015	0.051	0.051	0.0020	0.0017	0.0051	0.0020								

**Date: 1/22/13; outside spigot****E301F55**

Flow rate = 2.66 gpm

pH = 9.74 / 9.76

Units	Parameter	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01 1/2 Liter	Result	0.0290	0.0034	0.130	0.051	0.0210	0.0080	0.0051	0.5600
2	#02 1 Liter	Result	0.0230	0.0120	0.051	0.051	0.0200	0.0150	0.0051	0.0200
3	#03 1 Liter	Result	0.0450	0.0220	0.051	0.051	0.0048	0.0047	0.0051	0.0140
4	#04 1 Liter	Result	0.0390	0.0190	0.051	0.051	0.0023	0.0018	0.0051	0.0140
5	#05 1 Liter	Result	0.0120	0.0027	0.072	0.051	0.0017	0.0016	0.0051	0.0099
6	#06 1 Liter	Result	0.0035	0.0010	0.065	0.051	0.0014	0.0011	0.0051	0.0067
7	#07 3 min 1 Liter	Result	0.0022	0.0010	0.064	0.051	0.0010	0.0010	0.0051	0.0051



Date: 2/18/13; inside faucet

[illegible]

Date: 2/22/13; outside spigot

Flow rate = 2.82 gpm  
pH = 9.69 / 9.77

Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Parameter	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc	
1 #01, 1/2 Liter	0.0240	0.0022	0.0860	0.0510	0.0160	0.0110	0.0051	0.0024	0.6800	
2 #02, 1 Liter	0.0300	0.0086	0.0510	0.0510	0.0025	0.0022	0.0051	0.0020	0.0210	
3 #03, 3 min 1 Liter	0.0018	0.0010	0.0620	0.0510	0.0010	0.0012	0.0051	0.0020	0.0150	

## Date: 2/25/13; outside spigot E302H06

Flow rate = 2.89 gpm  
pH = 9.87 / 9.91

[illegible]

Date: 2/28/13; inside faucet

Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Parameter	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc
1	0.0096	0.0044	0.0510	0.0510	0.0280	0.0180	0.0051	0.0020	0.0160
2	0.0370	0.0170	0.0510	0.0510	0.0025	0.0018	0.0051	0.0020	0.0140
3	0.0019	0.0010	0.0510	0.0510	0.0011	0.0010	0.0051	0.0020	0.0092

## Date: 3/4/13; outside spigot

E303295

ATP = 582 ME/mL      Flow rate = 3.12 gpm

AIP = 582 ME/mL		Flow rate = 3.12 gpm			pH = 9.82 / 9.94			temp = 12.8 / 9.1		
Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Parameter	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Copper	Manganese	Zinc
1	0.0093	0.0022	0.0540	0.0510	0.0230	0.0140	0.0051	0.0020	0.0020	0.1100
2	0.0370	0.0180	0.0510	0.0510	0.0020	0.0016	0.0051	0.0020	0.0020	0.0230
3	0.0017	0.0010	0.0550	0.0510	0.0010	0.0010	0.0051	0.0020	0.0020	0.0130

Date: 3/7/13; inside spigot

E303641

Units	ppm	ppm
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	Units		ppm	Diss Lead	Iron	ppm	pH	Copper	ppm	Diss Copper	Tin	Manganese	Zinc
	Parameter	Lead	0.0100	0.0045	0.0510	0.0510		0.0240	0.0160	0.0051	0.0020	0.0180	
2			0.0063	0.0010	0.1200	0.0510		0.0016	0.0012	0.0051	0.0025	0.0310	
3			0.0120	0.0010	17.0000	0.2100		0.0110	0.0089	0.0050	0.1800	0.0280	

Date: 4/2/13; outside faucet

E304340

ATP = 1782 ME/mL      Flow rate = 2.04 gpm

ATP = 1782 ME/mL		Flow rate = 2.04 gpm		pH = 9.18 / 9.19		temp = 12.9 / 11.1	
Units	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Parameter	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin
1	0.0910	0.0073	0.8500	0.0510	0.0280	0.0054	0.0110 1.8000
2	0.0420	0.0250	0.0510	0.0510	0.0018	0.0014	0.0020 0.0240
3	0.0025	0.0012	0.0510	0.0510	0.0010	0.0010	0.0020 0.0110

# Loc #4, 56 Gentian Ave

Date: 1/15/13; inside faucet

E301A44

Flow rate = 1.48 gpm

pH = 9.50 / 9.59

Sample#:	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0077	0.0019	0.051	0.051	0.051	0.0220	0.0150	0.0051	0.002 0.0220
2 #02, 1/2 Liter	0.0080	0.0025	0.051	0.051	0.051	0.0120	0.0088	0.0051	0.002 0.0051
3 #03, 1 Liter	0.0055	0.0010	0.120	0.051	0.051	0.0140	0.0059	0.0051	0.002 0.0240
4 #04, 1 Liter	0.0081	0.0012	0.130	0.051	0.051	0.0052	0.0034	0.0051	0.002 0.0190
5 #05, 1 Liter	0.0042	0.0012	0.051	0.051	0.051	0.0024	0.0018	0.0051	0.002 0.0300
6 #06, 1 Liter	0.0021	0.0010	0.051	0.051	0.051	0.0024	0.0020	0.0051	0.002 0.0200
7 #07, 1 Liter	0.0019	0.0010	0.051	0.051	0.051	0.0021	0.0021	0.0051	0.002 0.0180
8 #08, 1 Liter	0.0013	0.0010	0.051	0.051	0.051	0.0012	0.0012	0.0051	0.002 0.0180
9 #09, 1 Liter	0.0013	0.0010	0.051	0.051	0.051	0.0010	0.0010	0.0051	0.002 0.0220
10 #10, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.051	0.0010	0.0010	0.0051	0.002 0.0150

Date: 1/17/13; outside spigot

E301C76

Flow rate = 1.30 gpm

pH = 9.84 / 9.91

Sample#:	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #02, 1/2 Liter	0.0150	0.0078	0.051	0.051	0.051	0.0043	0.0031	0.0051	0.002 0.0080
2 #03, 1 Liter	0.0039	0.0016	0.051	0.051	0.051	0.0028	0.0024	0.0051	0.002 0.0190
3 #04, 1 Liter	0.0034	0.0010	0.051	0.051	0.051	0.0017	0.0016	0.0051	0.002 0.0170
4 #05, 1 Liter	0.0019	0.0010	0.051	0.051	0.051	0.0011	0.0010	0.0051	0.002 0.0310
5 #06, 1 Liter	0.0015	0.0010	0.051	0.051	0.051	0.0010	0.0010	0.0051	0.002 0.0170
6 #07, 1 Liter	0.0016	0.0010	0.051	0.051	0.051	0.0010	0.0012	0.0051	0.002 0.0170
7 #08, 1 Liter	0.0014	0.0010	0.051	0.051	0.051	0.0010	0.0010	0.0051	0.002 0.0220
8 #09, 1 Liter	0.0013	0.0010	0.051	0.051	0.051	0.0010	0.0010	0.0051	0.002 0.0160
9 #10, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.051	0.0010	0.0012	0.0051	0.002 0.0051

# Date: 1/23/13; outside spigot E301G28

Flow rate = 1.38 gpm pH = 9.61 / 9.75

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0170	0.0055	0.051	0.051	0.0090	0.0054	0.0051	0.002	0.0051
2 #02, 1 Liter	0.0086	0.0033	0.051	0.051	0.0052	0.0034	0.0051	0.002	0.0091
3 #03, 1 Liter	0.0110	0.0030	0.051	0.051	0.0018	0.0013	0.0051	0.002	0.0051
4 #04, 1 Liter	0.0036	0.0010	0.051	0.051	0.0014	0.0011	0.0051	0.002	0.0051
5 #05, 1 Liter	0.0016	0.0010	0.051	0.051	0.0013	0.0010	0.0051	0.002	0.0051
6 #06, 1 Liter	0.0014	0.0010	0.051	0.051	0.0012	0.0010	0.0051	0.002	0.0051
7 #07, 1 Liter	0.0014	0.0010	0.051	0.051	0.0010	0.0011	0.0051	0.002	0.0051
8 #08, 1 Liter	0.0013	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.002	0.0051
9 #09, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.002	0.0051

# Date: 1/25/13; outside spigot E301H02

Flow rate = 1.52 gpm pH = 9.66 / 9.79

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0084	0.0019	0.051	0.051	0.0200	0.0080	0.0051	0.002	0.0300
2 #02, 1 Liter	0.0110	0.0030	0.051	0.051	0.0120	0.0062	0.0051	0.002	0.0330
3 #03, 1 Liter	0.0180	0.0038	0.051	0.051	0.0022	0.0016	0.0051	0.002	0.0051
4 #04, 1 Liter	0.0044	0.0010	0.051	0.051	0.0016	0.0013	0.0051	0.002	0.0051
5 #05, 1 Liter	0.0016	0.0010	0.051	0.051	0.0016	0.0018	0.0051	0.002	0.0051
6 #06, 1 Liter	0.0014	0.0010	0.051	0.051	0.0013	0.0013	0.0051	0.002	0.0051
7 #07, 1 Liter	0.0014	0.0010	0.051	0.051	0.0022	0.0023	0.0051	0.002	0.0051
8 #08, 1 Liter	0.0014	0.0010	0.051	0.051	0.0010	0.0012	0.0051	0.002	0.0051
9 #09, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.002	0.0051

# **Date: 1/28/13; outside spigot E301H38**

Flow rate = 1.57 gpm pH = 9.52 / 9.72

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0230	0.0077	0.055	0.051	0.0250	0.0200	0.0051	0.002	0.0051
2 #02, 1 Liter	0.0180	0.0100	0.051	0.051	0.0170	0.0140	0.0051	0.002	0.0190
3 #03, 1 Liter	0.0300	0.0160	0.051	0.051	0.0030	0.0025	0.0051	0.002	0.0051
4 #04, 1 Liter	0.0063	0.0020	0.051	0.051	0.0022	0.0015	0.0051	0.002	0.0051
5 #05, 1 Liter	0.0017	0.0010	0.051	0.051	0.0016	0.0014	0.0051	0.002	0.0051
6 #06, 1 Liter	0.0015	0.0012	0.051	0.051	0.0019	0.0016	0.0051	0.002	0.0051
7 #07, 1 Liter	0.0014	0.0010	0.051	0.051	0.0012	0.0010	0.0051	0.002	0.0051
8 #08, 1 Liter	0.0013	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.002	0.0051
9 #09, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.0010	0.0012	0.0051	0.002	0.0051

# **Date: 2/11/13; outside faucet E302594**

Flow rate = 1.82 gpm pH = 9.74 / 9.78 temp = 3.4 / 2.8

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0041	0.001	0.051	0.051	0.0055	0.0034	0.0051	0.002	0.0051
2 #02, 1 Liter **	0.0013	0.001	0.051	0.051	0.0012	0.0012	0.0051	0.002	0.0088
3 #03, 3 min 1 Liter	0.001	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0087

# **Date: 2/12/13; inside spigot E302694**

Flow rate = 1.90 gpm pH = 9.71 / 9.72

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.011	0.001	0.055	0.051	0.0045	0.0025	0.0051	0.002	0.0051
2 #02, 1 Liter **	0.0013	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0096
3 #03, 3 min 1 Liter	0.001	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0092



## Date: 2/18/13; inside faucet

E302A72

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc
1 #01, 1/2 Liter	0.0100	0.0022	0.0510	0.0510	0.0061	0.0041		0.0051	0.0020
2 #02, 1 Liter **	0.0012	0.0010	0.0510	0.0510	0.0010	0.0010		0.0051	0.0020
3 #03, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010		0.0051	0.0020

## Date: 2/19/13; outside spigot

E302C07

Flow rate = 0.88 gpm

$$\text{pH} = 9.75 / 9.82$$

temp=10.2/6.7

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc
1 #01, 1/2 Liter	0.0110	0.0020	0.0510	0.0510	0.0045	0.0022	0.0051	0.0020	0.0056
2 #02, 1 Liter **	0.0018	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0096
3 #03, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0091

## Date: 2/25/13; outside spigot

E302G22

$$\text{Flow rate} = 1.21 \text{ gpm}$$

pH = 9.82 / 9.97

temp=13.9/8.9

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0100	0.0039	0.0510	0.0510	0.0098	0.0089	0.0051	0.0020	0.0051
2	0.0100	0.0014	0.0510	0.0510	0.0014	0.0020	0.0051	0.0020	0.0094
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0093

Date: 2/26/13; inside faucet

**E302H08**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	<b>0.011</b>	0.0031		0.051		<b>0.01</b>	<b>0.0069</b>	0.0051	0.002
2	0.007	<b>0.0034</b>		0.051		0.0014	0.0013	0.0051	<b>0.0093</b>
3	0.001	0.001		0.051		0.001	0.001	0.0051	0.002

**Date: 3/4/13; outside spigot****E303185**

ATP = 256 ME/mL Flow rate = 1.15 gpm

pH = 9.90 / 9.99 temp = 10.2 / 8.4

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0080	0.0050	0.0510	0.0510	0.0120	0.0092	0.0051	0.0020	0.0060
2	0.0120	0.0060	0.0510	0.0510	0.0016	0.0014	0.0051	0.0020	0.0120
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0089

**Date: 3/5/13; inside faucet****E303293**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0096	0.0037	0.0510	0.0510	0.0150	0.0100	0.0051	0.0020	0.0051
2	0.0093	0.0032	0.0510	0.0510	0.0018	0.0019	0.0051	0.0020	0.0120
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0091

**Date: 4/2/13; outside faucet****E304159**

ATP = 145 ME/mL Flow rate = 1.33 gpm

pH = 10.12 / 9.80 temp = 9.7 / 7.6

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0027	0.0010	0.0510	0.0510	0.0044	0.0033	0.0020	0.0020	0.0150
2	0.0059	0.0026	0.0510	0.0510	0.0010	0.0010	0.0020	0.0020	0.0120
3	0.0013	0.0010	0.0510	0.0510	0.0010	0.0010	0.0020	0.0020	0.0180

**Date: 4/8/13; inside faucet****E304643**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0110	0.0052	0.0510	0.0510	0.0093	0.0071	0.0020	0.0020	0.0051
2	0.0079	0.0038	0.0510	0.0510	0.0098	0.0072	0.0020	0.0020	0.0140
3	0.0013	0.0010	0.0510	0.0510	0.0010	0.0010	0.0020	0.0020	0.0110

# Loc # 5, 42 Harkness Street

Date: 1/8/13; outside spigot E301630

Flow rate =

pH = 9.66 / 9.79

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0110	0.0065	0.051	0.051	0.0470	0.0330	0.0051	0.0036	0.0180
2 #02, 1/2 Liter	0.0083	0.0039	0.051	0.051	0.0690	0.0290	0.0051	0.0034	0.0067
3 #03, 1 Liter	0.0038	0.0023	0.051	0.051	0.0460	0.0280	0.0051	0.0027	0.0270
4 #04, 1 Liter	0.0220	0.0150	0.051	0.051	0.0059	0.0046	0.0051	0.0022	0.0190
5 #05, 1 Liter	0.0150	0.0093	0.051	0.051	0.0021	0.0019	0.0051	0.0020	0.0051
6 #06, 3 min 1 Liter	0.0019	0.0010	0.051	0.051	0.0059	0.0043	0.0051	0.0020	0.0051

Date: 1/9/13; outside spigot E301689

Flow rate = 2.20 gpm

pH = 9.44 / 9.57

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0150	0.0061	0.051	0.051	0.1000	0.0300	0.0051	0.0020	0.0150
2 #02, 1/2 Liter	0.0067	0.0017	0.051	0.051	0.0460	0.0240	0.0051	0.0020	0.0051
3 #03, 1 Liter	0.0150	0.0088	0.051	0.051	0.0140	0.0099	0.0051	0.0020	0.0730
4 #04, 1 Liter	0.0330	0.0190	0.051	0.051	0.0021	0.0016	0.0051	0.0020	0.0058
5 #05, 1 Liter	0.0047	0.0010	0.051	0.051	0.0014	0.0012	0.0051	0.0041	0.0051
6 #06, 3 min 1 Liter	0.0017	0.0010	0.051	0.051	0.0031	0.0019	0.0051	0.0042	0.0062

Date: 1/23/13; inside faucet

Flow rate = 0.99 gpm

pH = 9.43 / 9.40

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0028	0.0010	0.051	0.051	0.0099	0.0091	0.0051	0.0020	0.0540
2 #02, 1 Liter	0.0026	0.0012	0.051	0.051	0.0130	0.0094	0.0051	0.0020	0.0560
3 #03, 1 Liter	0.0029	0.0017	0.051	0.051	0.0200	0.0160	0.0051	0.0020	0.0160
4 #04, 1 Liter	0.0084	0.0026	0.051	0.051	0.0150	0.0100	0.0051	0.0020	0.0480
5 #05, 1 Liter	0.0280	0.0170	0.051	0.051	0.0034	0.0028	0.0051	0.0020	0.0160
6 #06, 1 Liter	0.0096	0.0028	0.055	0.051	0.0018	0.0015	0.0051	0.0026	0.0051
7 #07, 3 min 1 Liter	0.0010	0.0010	0.064	0.051	0.0010	0.0010	0.0051	0.0029	0.0051

## Date: 1/25/13; outside spigot E301G94

$$\text{Flow rate} = 3.31 \text{ gpm}$$

pH = 9.37 / 9.63

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0360	0.0100	0.120	0.051	0.0230	0.0110	0.0051	0.0023	0.0910
2 #02, 1 Liter	0.0220	0.0074	0.094	0.051	0.0046	0.0024	0.0051	0.0030	0.0051
3 #03, 1 Liter	0.0013	0.0010	0.065	0.051	0.0027	0.0025	0.0051	0.0032	0.0051
4 #04, 1 Liter	0.0011	0.0010	0.064	0.051	0.0020	0.0012	0.0051	0.0031	0.0051
5 #05, 3 min 1 Liter	0.0010	0.0010	0.058	0.051	0.0010	0.0010	0.0051	0.0031	0.0051

## Date: 1/30/13; outside spigot E301J95

flow rate = 2.95 gpm

pH = 9.25 / 9.61

	ppm	Diss Lead	Iron	pptm	Copper	pptm	Diss Copper	Tin	pptm	Manganese	Zinc
1 #01, 1/2 Liter	<b>0.0150</b>	0.0023	<b>0.0520</b>	0.0510	<b>0.0940</b>	<b>0.0300</b>	0.0051	0.0020	0.0092		
2 #02, 1 Liter	0.0120	<b>0.0059</b>	0.0510	0.0510	<b>0.0460</b>	<b>0.0200</b>	0.0051	0.0020	<b>0.0780</b>		
3 #03, 1 Liter	<b>0.0300</b>	<b>0.0160</b>	0.0510	0.0510	0.0033	0.0028	0.0051	0.0020	<b>0.0160</b>		
4 #04, 1 Liter	0.0057	0.0010	0.0510	0.0510	0.0022	0.0027	0.0051	0.0020	0.0110		
5 #05, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0010	0.0014	0.0051	0.0020	0.0130		

E302845

Flow rate = 1.00 gpm

pH = 9.49 / 9.48

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc			
1	#01, 1/2 Liter	0.0021	0.001	0.051	0.051	<b>0.011</b>	<b>0.0072</b>	0.0051	0.002	<b>0.055</b>		
2	#02, 1 Liter	<b>0.02</b>	<b>0.0087</b>	0.051	0.051	0.0072	0.004	0.0051	0.002	0.046		
3	#03, 3 min 1 Liter	0.001	0.001	0.051	0.051	0.002	0.0012	0.0051	0.002	0.011		

Date: 2/15/13; outside spigot

**E302A02**

Flow rate = 2.51 gpm

pH = 9.56 / 9.70

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temp=18.0/14.5
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	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.016	0.0021	0.051	0.051	0.75	0.038	0.0051	0.002	0.01
2 #02, 1 Liter	0.024	0.014	0.051	0.051	0.0093	0.0059	0.0051	0.002	0.041
3 #03, 3 min 1 Liter	0.001	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0091

Date: 2/22/13; outside spigot

E302F63

Flow rate = 3.06 gpm

pH = 9.59 / 9.86

temp = 15.4 / 10.1

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0100	0.0030	0.0510	0.0510	<b>0.1300</b>	<b>0.0520</b>	0.0051	0.0020	0.0088
2 #02, 1 Liter	<b>0.0240</b>	<b>0.0140</b>	0.0510	0.0510	0.0069	0.0038	0.0051	<b>0.0046</b>	<b>0.0590</b>
3 #03, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0010	0.0011	0.0051	0.0020	0.0092

Date: 2/27/13; outside spigot

E302127

ATP = 95 ME/mL

Flow rate = 3.01 gpm

$\text{pH} = 9.67 / 9.87$

$$\text{temp} = 16.6 / 10.3$$

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0036	0.0010	0.0510	0.0510	<b>0.0830</b>	<b>0.0260</b>	0.0051	0.0020	0.0063
2	<b>0.0240</b>	<b>0.0130</b>	0.0510	0.0510	0.0030	0.0020	0.0051	0.0020	<b>0.0140</b>
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	<b>0.0030</b>	0.0097

**Date: 3/1/13; inside spigot****E303080**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0016	0.0010	0.0510	0.0081	0.0059	0.0510	0.0051	0.0020	0.0640
2	0.0190	0.0130	0.0510	0.0079	0.0040	0.0510	0.0051	0.0020	0.0510
3	0.0010	0.0010	0.0510	0.0023	0.0011	0.0510	0.0051	0.0020	0.0099

**Date: 3/6/13; outside spigot****E303459**

ATP = 345 ME/mL		Flow rate = 3.73 gpm				pH = 9.72 / 9.87		temp = 16.3 / 10.9	
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc
1	0.0170	0.0013	0.0680	0.0510	0.0960	0.0240	0.0051	0.0020	0.0110
2	0.0240	0.0140	0.0510	0.0510	0.0058	0.0045	0.0051	0.0020	0.0160
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0100

**Date: 3/8/13; inside spigot****E303639**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0016	0.0010	0.0510	0.0510	0.0073	0.0056	0.0051	0.0020	0.0610
2	0.0180	0.0120	0.0510	0.0510	0.0041	0.0030	0.0051	0.0020	0.0480
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0100

**Date: 4/8/13; outside spigot****E304642**

ATP = 1904 ME/mL		Flow rate = 2.91 gpm				pH = 10.02 / 10.16		temp = 13.8 / 12.2	
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead		Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc
1	0.0200	0.0047	0.0510	0.0510	2.9000	0.3800		0.0020	0.0200
2	0.0270	0.0180	0.0510	0.0510	0.0250	0.0120		0.0020	0.0330
3	0.0011	0.0010	0.0510	0.0510	0.0014	0.0011		0.0020	0.0091

Date: 4/12/13; inside spigot

E304A65

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0029	0.0014	0.0510	0.0510	0.0072	0.0058		0.0020	0.0370
2	0.0025	0.0010	0.0510	0.0510	0.0190	0.0060		0.0020	0.0180
3	0.0016	0.0010	0.0510	0.0510	0.0010	0.0010		0.0020	0.0110

# Loc #6, 104 Shaw Ave

Date: 1/11/13; inside faucet

E301808

Flow rate = 1.30 gpm pH = 9.43 / 9.60

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0780	0.0042	0.16	0.051	0.3200	0.0160	0.0051	0.0025	3.3000
2 #02, 1/2 Liter	0.0085	0.0010	0.12	0.051	0.0570	0.0190	0.0051	0.0020	0.0900
3 #03, 1 Liter	0.0086	0.0021	0.11	0.051	0.0550	0.0250	0.0051	0.0020	0.0350
4 #04, 1 Liter	0.0092	0.0023	0.11	0.051	0.0460	0.0220	0.0051	0.0020	0.0160
5 #05, 1 Liter	0.0250	0.0055	0.10	0.051	0.0290	0.0130	0.0051	0.0020	0.0150
6 #06, 1 Liter	0.0360	0.0043	0.11	0.051	0.0140	0.0062	0.0051	0.0020	0.0140
7 #07, 1 Liter	0.0510	0.0087	0.11	0.051	0.0064	0.0029	0.0051	0.0020	0.0340
8 #08, 1 Liter	0.0580	0.0090	0.12	0.051	0.0032	0.0017	0.0051	0.0020	0.0210
9 #09, 1 Liter	0.0580	0.0088	0.14	0.051	0.0034	0.0018	0.0051	0.0020	0.0280
10 #10, 1 Liter	0.0500	0.0065	0.20	0.051	0.0026	0.0014	0.0051	0.0020	0.0060
11 #11, 1 Liter	0.0310	0.0035	0.24	0.051	0.0024	0.0022	0.0051	0.0031	0.0220
12 #12, 1 Liter	0.0100	0.0011	0.29	0.051	0.0021	0.0014	0.0051	0.0042	0.0210
13 #13, 3 min 1 Liter	0.0026	0.0010	0.30	0.058	0.0015	0.0010	0.0051	0.0044	0.0240



**Date: 1/17/13; outside spigot****E301C78**

Flow rate = 1.80 gpm pH = 9.61 / 9.78

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc				
1	#02, 1/2 Liter	0.0078	0.0014	0.36	0.051	0.1000	0.0300	0.0051	0.0033	0.0068			
2	#03, 1 Liter	0.0072	0.0032	0.18	0.062	0.0580	0.0350	0.0051	0.0021	0.0051			
3	#04, 1 Liter	0.0072	0.0029	0.13	0.051	0.0430	0.0250	0.0051	0.0020	0.0051			
4	#05, 1 Liter	0.0082	0.0037	0.13	0.051	0.0470	0.0290	0.0051	0.0020	0.0051			
5	#06, 1 Liter	0.0120	0.0014	0.12	0.051	0.0230	0.0100	0.0051	0.0020	0.0210			
6	#07, 1 Liter	0.0450	0.0077	0.11	0.051	0.0071	0.0036	0.0051	0.0020	0.0051			
7	#08, 1 Liter	0.0550	0.0140	0.12	0.051	0.0036	0.0022	0.0051	0.0020	0.0051			
8	#09, 1 Liter	0.0600	0.0190	0.12	0.051	0.0031	0.0020	0.0051	0.0020	0.0200			
9	#10, 1 Liter	0.0570	0.0200	0.12	0.051	0.0028	0.0019	0.0051	0.0020	0.0240			
10	#11, 1 Liter	0.0240	0.0070	0.21	0.057	0.0025	0.0014	0.0051	0.0030	0.0051			
11	#12, 3 min 1 Liter	0.0024	0.0010	0.25	0.051	0.0013	0.0010	0.0051	0.0041	0.0051			

**Date: 1/22/13; outside spigot****E301F56**

Flow rate = 1.15 gpm pH = 9.55 / 9.74

	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
	Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese	Zinc				
1	#01, 1/2 Liter	0.1400	0.0024	1.40	0.078	0.1400	0.0310	0.015	0.0065	0.0470			
2	#02, 1 Liter	0.0100	0.0031	0.32	0.062	0.0610	0.0260	0.0051	0.0025	0.0220			
3	#03, 1 Liter	0.0059	0.0011	0.32	0.058	0.0220	0.0077	0.0051	0.0034	0.0260			
4	#04, 1 Liter	0.0046	0.0026	0.31	0.074	0.0150	0.0066	0.0051	0.0037	0.0200			
5	#05, 1 Liter	0.0049	0.0010	0.30	0.051	0.0110	0.0037	0.0051	0.0033	0.0051			
6	#06, 1 Liter	0.0130	0.0027	0.30	0.056	0.0058	0.0025	0.0051	0.0035	0.0240			
7	#07, 1 Liter	0.0240	0.0070	0.30	0.082	0.0036	0.0023	0.0051	0.0034	0.0200			
8	#08, 1 Liter	0.0260	0.0049	0.29	0.051	0.0025	0.0017	0.0051	0.0035	0.0150			
9	#09, 1 Liter	0.0260	0.0066	0.29	0.068	0.0025	0.0020	0.0051	0.0034	0.0180			
10	#10, 1 Liter	0.0210	0.0048	0.27	0.057	0.0022	0.0017	0.0051	0.0034	0.0051			
11	#11, 3 min 1 Liter	0.0025	0.0010	0.24	0.072	0.0014	0.0010	0.0051	0.0033	0.0051			

**Date: 1/24/13; outside spigot****E301G91**

Flow rate = 1.12 gpm pH = 9.68 / 9.86

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01 1/2 Liter	0.0900	0.0010	3.20	0.051	0.1900	0.0087	0.005	0.0220	0.0680
2 #02 1 Liter	0.0160	0.0031	0.47	0.086	0.0710	0.0310	0.0051	0.0045	0.0250
3 #03 1 Liter	0.0110	0.0039	0.18	0.063	0.0570	0.0290	0.0051	0.0022	0.0120
4 #04 1 Liter	0.0110	0.0056	0.17	0.074	0.0560	0.0360	0.0051	0.0020	0.0091
5 #05 1 Liter	0.0140	0.0061	0.15	0.058	0.0400	0.0250	0.0051	0.0020	0.0053
6 #06 1 Liter	0.0420	0.0080	0.14	0.051	0.0160	0.0095	0.0051	0.0020	0.0051
7 #07 1 Liter	0.0810	0.0160	0.14	0.051	0.0060	0.0041	0.0051	0.0020	0.0051
8 #08 1 Liter	0.0900	0.0210	0.14	0.051	0.0035	0.0025	0.0051	0.0020	0.0051
9 #09 1 Liter	0.0940	0.0140	0.14	0.051	0.0033	0.0019	0.0051	0.0020	0.0051
10 #10 1 Liter	0.0740	0.0260	0.16	0.051	0.0049	0.0031	0.0051	0.0020	0.0051
11 #11 3 min 1 Liter	0.0026	0.0010	0.24	0.051	0.0013	0.0011	0.0051	0.0030	0.0051

**Date: 1/29/13; outside spigot****E301I73**

Flow rate = 1.35 gpm pH = 9.62 / 9.85

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01 1/2 Liter	0.0620	0.0010	1.60	0.051	0.1400	0.0110	0.005	0.0081	0.0260
2 #02 1 Liter	0.0450	0.0044	0.55	0.064	0.1000	0.0300	0.0051	0.0043	0.0260
3 #03 1 Liter	0.0170	0.0047	0.24	0.066	0.0610	0.0370	0.0051	0.0022	0.0140
4 #04 1 Liter	0.0240	0.0043	0.20	0.053	0.0620	0.0270	0.0051	0.0021	0.0160
5 #05 1 Liter	0.0220	0.0049	0.16	0.051	0.0420	0.0160	0.0051	0.0020	0.0130
6 #06 1 Liter	0.0510	0.0100	0.15	0.051	0.0150	0.0056	0.0051	0.0021	0.0120
7 #07 1 Liter	0.0770	0.0150	0.12	0.051	0.0049	0.0021	0.0051	0.0020	0.0150
8 #08 1 Liter	0.0850	0.0180	0.13	0.051	0.0033	0.0020	0.0051	0.0020	0.0095
9 #09 1 Liter	0.0860	0.0160	0.13	0.051	0.0033	0.0019	0.0051	0.0020	0.0090
10 #10 1 Liter	0.0590	0.0120	0.18	0.051	0.0028	0.0015	0.0051	0.0026	0.0100
11 #11 3 min 1 Liter	0.0025	0.0010	0.29	0.056	0.0013	0.0010	0.0051	0.0046	0.0085

**Date: 2/14/13; inside faucet****E302954**

Flow rate = 1.24 gpm pH = 9.60 / 9.70

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0089	0.001	0.12	0.051	0.059	0.017	0.0051	0.002	0.0051
2 #02, 1 Liter	0.045	0.0043	0.11	0.051	0.003	0.0029	0.0051	0.002	0.01
3 #03, 3 min 1 Liter	0.0023	0.001	0.23	0.053	0.0015	0.001	0.0051	0.0039	0.0091

**Date: 2/15/13; outside spigot****E302999**

Flow rate = 1.15 gpm pH = 9.60 / 9.72

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0180	0.0012	1.5000	0.0510	0.1200	0.0220	0.0050	0.0056	0.0150
2 #02, 1 Liter	0.0560	0.0110	0.1200	0.0510	0.0053	0.0030	0.0051	0.0020	0.0120
3 #03, 3 min 1 Liter	0.0021	0.0010	0.2700	0.0510	0.0013	0.0012	0.0051	0.0033	0.0087

**Date: 2/19/13; outside spigot****E302C08**

Flow rate = 1.08 gpm pH = 9.67 / 9.78

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.015	0.0028	0.71	0.057	0.13	0.032	0.005	0.0031	0.0062
2 #02, 1 Liter	0.039	0.01	0.091	0.051	0.0046	0.0025	0.0051	0.002	0.0091
3 #03, 3 min 1 Liter	0.003	0.001	0.24	0.056	0.002	0.001	0.0051	0.0031	0.0085

**Date: 2/22/13; inside faucet****E302F61**

Flow rate = 1.24 gpm pH = 9.60 / 9.70

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0100	0.0038	0.0930	0.0510	0.0470	0.0260	0.0051	0.0020	0.0051
2 #02, 1 Liter	0.0280	0.0035	0.1600	0.0510	0.0026	0.0012	0.0051	0.0024	0.0110
3 #03, 3 min 1 Liter	0.0021	0.0010	0.2400	0.0580	0.0014	0.0010	0.0051	0.0036	0.0100

**Date: 2/25/13; outside spigot****E302G21**

Flow rate = 1.03 gpm pH = 9.79 / 9.95

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0081	0.0010	0.7000	0.0510	0.1100	0.0170	0.0050	0.0028	0.0070
2	0.0240	0.0022	0.1200	0.0510	0.0044	0.0028	0.0051	0.0020	0.0095
3	0.0019	0.0019	0.1500	0.0580	0.0013	0.0015	0.0051	0.0025	0.0092

**Date: 2/28/13; inside faucet****E303078**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0160	0.0026	0.0970	0.0510	0.0380	0.0150	0.0051	0.0020	0.0051
2	0.0340	0.0110	0.0910	0.0510	0.0030	0.0020	0.0051	0.0020	0.0110
3	0.0022	0.0010	0.1400	0.0510	0.0014	0.0010	0.0051	0.0021	0.0100

**Date: 3/4/13; inside faucet****E303184**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0066	0.0030	0.0840	0.0510	0.0440	0.0270	0.0051	0.0020	0.0066
2	0.0480	0.0190	0.0780	0.0510	0.0032	0.0023	0.0051	0.0020	0.0120
3	0.0023	0.0010	0.2300	0.0510	0.0015	0.0010	0.0051	0.0033	0.0100

**Date: 3/6/13; outside spigot****E303460**

ATP = 437 ME/mL		Flow rate = 1.31 gpm		pH = 9.83 / 9.96		temp = 14.8 / 11.3	
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0079	0.0010	1.3000	0.0510	0.1400	0.0180	0.0050	0.0043 0.0240
0.0140	0.0029	0.1600	0.0510	0.0028	0.0019	0.0051	0.0025 0.0110
0.0020	0.0010	0.2200	0.0510	0.0012	0.0010	0.0051	0.0033 0.0097

**Date: 4/4/13; inside faucet****E304399**

ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0071	0.0010	0.1100	0.0510	0.0280	0.0140	0.0020	0.0051
0.0370	0.0045	0.1400	0.0510	0.0020	0.0012	0.0020	0.0100
0.0035	0.0010	0.2000	0.0510	0.0011	0.0010	0.0020	0.0100

**Date: 4/10/13; outside spigot****E304901**

ATP = 1453 ME/mL		Flow rate = 1.66 gpm		pH = 9.97 / 10.15		temp = 16.3 / 11.6	
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0140	0.0038	1.1000	0.1500	0.2800	0.0590	0.1200	0.0062
0.0170	0.0034	0.1400	0.0510	0.0026	0.0016	0.0020	0.0095
0.0034	0.0010	0.1800	0.0510	0.0015	0.0011	0.0020	0.0130

**Loc #7, 183 Laurel Hill Ave**

Date: 1/15/13: inside faucet

E301A41

Flow rate = 1.24 gpm

pH = 9.29 / 9.33

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
2	#02, 1/2 Liter	0.0068	0.0010	<b>0.097</b>	0.051	<b>0.0400</b>	<b>0.0160</b>	0.0051	<b>0.0030</b>	0.0085
3	#03, 1 Liter	0.0042	0.0010	<b>0.095</b>	0.051	0.0280	0.0150	0.0051	<b>0.0028</b>	0.0200
4	#04, 1 Liter	0.0044	0.0011	0.092	0.051	<b>0.0310</b>	<b>0.0160</b>	0.0051	<b>0.0028</b>	0.0210
5	#05, 1 Liter	0.0054	0.0013	0.090	0.051	0.0300	0.0140	0.0051	0.0027	0.0220
6	#06, 1 Liter	0.0078	0.0019	<b>0.095</b>	0.051	0.0190	0.0098	0.0051	0.0027	<b>0.0370</b>
7	#07, 1 Liter	<b>0.0370</b>	0.0044	0.092	0.051	0.0060	0.0035	0.0051	0.0023	<b>0.0300</b>
8	#08, 1 Liter	<b>0.0480</b>	<b>0.0097</b>	0.090	0.051	0.0028	0.0019	0.0051	0.0024	0.0180
9	#09, 1 Liter	0.0200	<b>0.0064</b>	0.058	0.051	0.0021	0.0020	0.0051	0.0020	0.0180
10	#10, 3 min 1 Liter	0.0013	0.0010	0.051	0.051	0.0013	0.0021	0.0051	0.0020	0.0180

Date: 1/18/13; outside spigot

E301D06

Flow rate = 1.49 gpm

pH = 9.59 / 9.72

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0030	0.0010	0.051	0.051	<b>0.0300</b>	<b>0.0200</b>	0.0051	0.0020	0.0069
2	#02, 1 Liter	0.0034	0.0030	0.051	0.051	<b>0.0310</b>	<b>0.0220</b>	0.0051	0.0020	0.0051
3	#03, 1 Liter	0.0051	0.0029	0.051	0.051	<b>0.0300</b>	0.0180	0.0051	0.0020	<b>0.0340</b>
4	#04, 1 Liter	0.0096	0.0052	0.051	0.051	0.0200	0.0120	0.0051	0.0020	<b>0.0420</b>
5	#05, 1 Liter	<b>0.0280</b>	<b>0.0160</b>	0.051	0.051	0.0044	0.0040	0.0051	0.0020	0.0290
6	#06, 1 Liter	<b>0.0330</b>	<b>0.0150</b>	0.051	0.051	0.0020	0.0019	0.0051	0.0020	0.0220
7	#07, 1 Liter	0.0100	0.0037	0.051	0.051	0.0015	0.0014	0.0051	0.0020	0.0170
8	#08, 3 min 1 Liter	0.0012	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.0020	0.0190

# Date: 1/24/13; outside spigot E301G89

Flow rate = 1.56 gpm

pH = 9.61 / 9.70

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0120	0.0033	0.051	0.051	0.0360	0.0180	0.0051	0.0020	0.0460
2 #02, 1 Liter	0.0054	0.0030	0.051	0.051	0.0230	0.0180	0.0051	0.0020	0.0210
3 #03, 1 Liter	0.0110	0.0067	0.051	0.051	0.0110	0.0085	0.0051	0.0020	0.0150
4 #04, 1 Liter	0.0200	0.0130	0.051	0.051	0.0040	0.0034	0.0051	0.0020	0.0051
5 #05, 1 Liter	0.0150	0.0079	0.051	0.051	0.0019	0.0019	0.0051	0.0020	0.0051
6 #06, 1 Liter	0.0056	0.0014	0.051	0.051	0.0012	0.0014	0.0051	0.0020	0.0051
7 #07, 1 Liter	0.0024	0.0010	0.051	0.051	0.0016	0.0015	0.0051	0.0020	0.0051
8 #08, 3 min 1 Liter	0.0011	0.0010	0.051	0.051	0.0010	0.0014	0.0051	0.0020	0.0051

# Date: 1/25/13; outside spigot E301H00

Flow rate = 2.82 gpm

pH = 9.78 / 9.97

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0068	0.0013	0.055	0.051	0.0550	0.0260	0.0051	0.0020	0.0420
2 #02, 1 Liter	0.0057	0.0025	0.051	0.051	0.0320	0.0230	0.0051	0.0020	0.0160
3 #03, 1 Liter	0.0190	0.0088	0.051	0.051	0.0190	0.0120	0.0051	0.0020	0.0200
4 #04, 1 Liter	0.0370	0.0160	0.051	0.051	0.0050	0.0037	0.0051	0.0020	0.0120
5 #05, 1 Liter	0.0280	0.0079	0.051	0.051	0.0019	0.0017	0.0051	0.0020	0.0051
6 #06, 1 Liter	0.0100	0.0023	0.051	0.051	0.0014	0.0012	0.0051	0.0020	0.0051
7 #07, 1 Liter	0.0018	0.0010	0.051	0.051	0.0012	0.0010	0.0051	0.0020	0.0051
8 #08, 3 min 1 Liter	0.0011	0.0010	0.051	0.051	0.0010	0.0011	0.0051	0.0020	0.0051

**Date: 1/30/13; outside spigot****E301J96**

Flow rate = 2.38 gpm

pH = 9.58 / 9.68

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0031	0.0010	0.051	0.051	0.0370	0.0220	0.0051	0.0020	0.0092
2 #02, 1 Liter	0.0035	0.0015	0.051	0.051	0.0380	0.0200	0.0051	0.0020	0.0140
3 #03, 1 Liter	0.0043	0.0017	0.051	0.051	0.0320	0.0180	0.0051	0.0020	0.0140
4 #04, 1 Liter	0.0070	0.0030	0.051	0.051	0.0200	0.0120	0.0051	0.0020	0.0450
5 #05, 1 Liter	0.0300	0.0130	0.051	0.051	0.0035	0.0026	0.0051	0.0020	0.0190
6 #06, 1 Liter	0.0330	0.0130	0.051	0.051	0.0020	0.0031	0.0051	0.0020	0.0110
7 #07, 1 Liter	0.0057	0.0013	0.051	0.051	0.0013	0.0014	0.0051	0.0020	0.0110
8 #08, 3 min 1 Liter	0.0010	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.0020	0.0099

**Date: 2/11/13; inside faucet****E302596**

Flow rate = 1.22 gpm

pH = 9.43 / 9.51

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0095	0.0043	0.051	0.051	0.03	0.02	0.0051	0.002	0.007
2 #02, 1 Liter	0.03	0.014	0.051	0.051	0.0043	0.0031	0.0051	0.002	0.018
3 #03, 3 min 1 Liter	0.0011	0.001	0.051	0.051	0.0012	0.0011	0.0051	0.002	0.0089

**Date: 2/12/13; outside spigot****E302693**

Flow rate = 2.26 gpm

pH = 9.54 / 9.60

temp = 13.7 / 11.5

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0032	0.001	0.051	0.051	0.05	0.025	0.0051	0.002	0.012
2 #02, 1 Liter	0.027	0.01	0.051	0.051	0.0039	0.0032	0.0051	0.002	0.016
3 #03, 3 min 1 Liter	0.001	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0094



## Date: 2/18/13; inside faucet

**E302A73**

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0036	0.0020	0.0510	0.0510	0.0380	0.0260	0.0051	0.0020	0.0053
2	#02, 1 Liter	0.0320	0.0130	0.0510	0.0510	0.0047	0.0039	0.0051	0.0020	0.0220
3	#03, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0012	0.0010	0.0051	0.0020	0.0093

## Date: 2/20/13; outside spigot

**E302D42**

Flow rate = 2.26 gpm

$$\text{pH} = 9.69 / 9.81$$

temp = 11.8 / 9.0

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0041	0.0010	0.0510	0.0510	<b>0.0350</b>	<b>0.0190</b>	0.0051	0.0020	0.0110
2	#02, 1 Liter	<b>0.0230</b>	<b>0.0098</b>	0.0510	0.0510	0.0024	0.0018	0.0051	0.0020	<b>0.0190</b>
3	#03, 3 min 1 Liter	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	<b>0.0022</b>	0.0110

## Date: 2/25/13; inside faucet

**E302G20**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0032	0.0018	0.0510	<b>0.0430</b>	<b>0.0340</b>	0.0510	0.0051	0.0020	0.0063
2	<b>0.0160</b>	<b>0.0097</b>	0.0510	0.0093	0.0080	0.0510	0.0051	0.0020	<b>0.0250</b>
3	0.0010	0.0010	0.0510	0.0011	0.0010	<b>0.0540</b>	0.0051	<b>0.0022</b>	0.0100

## Date: 2/26/13; outside spigot

E302H05

Flow rate = 2.26 gpm

pH = 9.81 / 9.90

temp = 11.5 / 7.6

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	0.0026	0.0010	0.0510	0.0510	0.0360	0.0200	0.0051	0.0020	0.0200
2	0.0260	0.0110	0.0510	0.0510	0.0035	0.0026	0.0051	0.0020	0.0099
3	0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020	0.0093



**Loc #8, 70 Sandringham Ave**

Date: 1/10/13; inside faucet

89103  
E301688

Flow rate = 1.49 gpm

$$p_H = 9.33 / 9.53$$

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0110	0.0011	<b>0.230</b>	0.051	<b>0.0780</b>	<b>0.0140</b>	0.0051	<b>0.0089</b>	<b>0.0730</b>
2	#02, 1/2 Liter	0.0073	0.0010	<b>0.160</b>	0.051	0.0095	0.0045	0.0051	0.0056	0.0710
3	#03, 1 Liter	0.0086	0.0014	0.140	0.051	<b>0.0130</b>	<b>0.0063</b>	0.0051	0.0050	<b>0.1000</b>
4	#04, 1 Liter	0.0100	0.0014	0.150	0.051	0.0098	0.0047	0.0051	<b>0.0058</b>	0.0660
5	#05, 1 Liter	0.0310	0.0060	0.120	0.051	0.0041	0.0025	0.0051	0.0041	0.0150
6	#06, 1 Liter	<b>0.0600</b>	<b>0.0077</b>	0.140	0.051	0.0015	0.0010	0.0051	0.0045	0.0055
7	#07, 1 Liter	<b>0.0480</b>	<b>0.0073</b>	0.150	0.051	0.0028	0.0029	0.0051	0.0050	0.0051
8	#08, 1 Liter	0.0260	0.0030	0.170	0.051	0.0020	0.0011	0.0051	0.0057	0.0059
9	#09, 3 min 1 Liter	0.0082	0.0010	0.083	0.051	0.0450	0.0019	0.0051	0.0028	0.0580

Date: 1/11/13; outside spigot

E301807

Flow rate = 1.74 gpm

pH = 9.62 / 9.73

		ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1	#01, 1/2 Liter	0.0430	0.0059	0.150	0.051	0.1500	0.0390	0.0052	0.0043	0.7800
2	#02, 1/2 Liter	0.0099	0.0026	0.051	0.051	0.0120	0.0074	0.0051	0.0020	0.0390
3	#03, 1 Liter	0.0390	0.0170	0.051	0.051	0.0038	0.0024	0.0051	0.0020	0.0270
4	#04, 1 Liter	0.0460	0.0230	0.051	0.051	0.0020	0.0016	0.0051	0.0020	0.0190
5	#05, 1 Liter	0.0310	0.0110	0.051	0.051	0.0023	0.0017	0.0051	0.0020	0.0210
6	#06, 1 Liter	0.0093	0.0016	0.070	0.051	0.0016	0.0010	0.0051	0.0027	0.0190
7	#07, 3 min 1 Liter	0.0016	0.0010	0.062	0.051	0.0010	0.0010	0.0051	0.0032	0.0051

**Date: 1/15/13; outside spigot****E301A48**

Flow rate = 1.54 gpm

pH = 9.48 / 9.60

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0140	0.0071	0.056	0.051	0.0660	0.0420	0.0051	0.0026	0.0380
2 #02, 1/2 Liter	0.0083	0.0016	0.056	0.051	0.0120	0.0079	0.0051	0.0021	0.0550
3 #03, 1 Liter	0.0270	0.0130	0.051	0.051	0.0036	0.0033	0.0051	0.0020	0.0210
4 #04, 1 Liter	0.0420	0.0240	0.051	0.051	0.0012	0.0012	0.0051	0.0020	0.0260
5 #05, 1 Liter	0.0300	0.0130	0.051	0.051	0.0020	0.0016	0.0051	0.0020	0.0180
6 #06, 1 Liter	0.0120	0.0041	0.051	0.051	0.0012	0.0010	0.0051	0.0020	0.0170
7 #07, 3 min 1 Liter	0.0013	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.0020	0.0150

**Date: 1/17/13; outside spigot****E301C74**

Flow rate = 1.69 gpm

pH = 9.63 / 9.80

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #02, 1/2 Liter	0.0089	0.0012	0.063	0.051	0.0120	0.0075	0.0051	0.0037	0.0470
2 #03, 1 Liter	0.0270	0.0140	0.051	0.051	0.0040	0.0039	0.0051	0.0020	0.0290
3 #04, 1 Liter	0.0420	0.0250	0.051	0.051	0.0014	0.0013	0.0051	0.0020	0.0051
4 #05, 1 Liter	0.0300	0.0150	0.051	0.051	0.0017	0.0015	0.0051	0.0020	0.0051
5 #06, 1 Liter	0.0100	0.0052	0.051	0.051	0.0011	0.0013	0.0051	0.0020	0.0170
6 #07, 3 min 1 Liter	0.0013	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.0020	0.0160

**Date: 1/18/13; outside spigot****E301D08**

Flow rate = 1.86 gpm

pH = 9.60 / 9.82

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0088	0.0028	0.051	0.051	0.0140	0.0066	0.0051	0.0020	0.0400
2 #02, 1 Liter	0.0330	0.0200	0.051	0.051	0.0036	0.0024	0.0051	0.0020	0.0280
3 #03, 1 Liter	0.0400	0.0230	0.051	0.051	0.0019	0.0015	0.0051	0.0020	0.0051
4 #04, 1 Liter	0.0260	0.0100	0.051	0.051	0.0018	0.0014	0.0051	0.0020	0.0051
5 #05, 1 Liter	0.0067	0.0029	0.051	0.051	0.0012	0.0011	0.0051	0.0020	0.0210
6 #06, 3 min 1 Liter	0.0013	0.0010	0.051	0.051	0.0010	0.0010	0.0051	0.0020	0.0200

**Date: 2/12/13; inside spigot**

**E302846**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0072	0.0015	0.056	0.051	0.051	0.01	0.0059	0.0051	0.002
2 #02, 1 Liter	0.047	0.016	0.051	0.051	0.0052	0.0028	0.0051	0.002	0.016
3 #03, 3 min 1 Liter	0.0013	0.001	0.051	0.051	0.0023	0.001	0.0051	0.002	0.011
4 #04, 3 min 1 Liter	0.0011	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.012

**Date: 2/13/13; outside spigot**

**E302846**

Flow rate = 2.24 gpm      pH = 9.69 / 9.78      temp = 10.3 / 8.7									
	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.034	0.003	0.077	0.051	0.051	0.025	0.022	0.0051	0.002
2 #02, 1 Liter	0.043	0.019	0.051	0.051	0.002	0.0015	0.0051	0.002	0.014
3 #03, 3 min 1 Liter	0.0011	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.0084
4 #04, 3 min 1 Liter	0.0011	0.001	0.051	0.051	0.001	0.001	0.0051	0.002	0.009

**Date: 2/21/13; inside spigot**

**E302E19**

	ppm Lead	ppm Diss Lead	ppm Iron	ppm Diss Iron	ppm Copper	ppm Diss Copper	ppm Tin	ppm Manganese	ppm Zinc
1 #01, 1/2 Liter	0.0044	0.0010	0.0560	0.0510	0.0088	0.0052	0.0051	0.0020	0.0530
2 #02, 1 Liter	0.0310	0.0087	0.0520	0.0510	0.0066	0.0022	0.0051	0.0020	0.0210
3 #03, 3 min 1 Liter	0.0012	0.0010	0.0550	0.0510	0.0010	0.0010	0.0051	0.0028	0.0110
4 #04, 3 min 1 Liter	0.0010	0.0010	0.0520	0.0510	0.0010	0.0010	0.0051	0.0029	0.0110



**Date: 3/5/13; outside spigot****E303456**

ATP = 214 ME/mL		Flow rate = 1.87 gpm		pH = 9.85 / 10.02		temp = 14.4 / 9.3	
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0099	0.0023	0.0580	0.0510	0.0210	0.0110	0.0051	0.0020 0.0970
0.0390	0.0180	0.0510	0.0510	0.0017	0.0012	0.0051	0.0020 0.1900
0.0011	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020 0.0087
0.0010	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020 0.0090

**Date: 3/6/13; inside spigot****E303458**

ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0029	0.0010	0.0510	0.0510	0.0073	0.0056	0.0051	0.0020 0.0520
0.0230	0.0140	0.0510	0.0510	0.0038	0.0019	0.0051	0.0020 0.0140
0.0012	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020 0.0096
0.0011	0.0010	0.0510	0.0510	0.0010	0.0010	0.0051	0.0020 0.0100

**Date: 4/9/13; outside spigot****E304A25**

ATP = 4312 ME/mL		Flow rate = 1.71 gpm		pH = 9.45 / 9.54		temp = 18.6 / 14.1	
ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0170	0.0026	0.0510	0.0510	0.0083	0.0058	0.0020	0.0520
0.0340	0.0220	0.0510	0.0510	0.0012	0.0011	0.0020	0.0084
0.0017	0.0010	0.0510	0.0510	0.0010	0.0010	0.0020	0.0070


**Date: 4/12/13; inside spigot****E304A66**

ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
Lead	Diss Lead	Iron	Diss Iron	Copper	Diss Copper	Tin	Manganese Zinc
0.0016	0.0012	0.0510	0.0510	0.0061	0.0050	0.0020	0.0380
0.0260	0.0190	0.0510	0.0510	0.0028	0.0024	0.0020	0.0320
0.0014	0.0010	0.0550	0.0510	0.0015	0.0010	0.0020	0.0110

## Tailored Collaboration

# Galvanic Corrosion Following Partial Lead Service Line Replacement

Web Report #4349

 Subject Area: Infrastructure





# Galvanic Corrosion Following Partial Lead Service Line Replacement



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## FOREWORD

The Water Research Foundation (Foundation) is a nonprofit corporation dedicated to the development and implementation of scientifically sound research designed to help drinking water utilities respond to regulatory requirements and address high-priority concerns. The Foundation's research agenda is developed through a process of consultation with Foundation subscribers and other drinking water professionals. The Foundation's Board of Trustees and other professional volunteers help prioritize and select research projects for funding based upon current and future industry needs, applicability, and past work. The Foundation sponsors research projects through the Focus Area, Emerging Opportunities, and Tailored Collaboration programs, as well as various joint research efforts with organizations such as the U.S. Environmental Protection Agency and the U.S. Bureau of Reclamation.

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A broad spectrum of water supply issues is addressed by the Foundation's research agenda, including resources, treatment and operations, distribution and storage, water quality and analysis, toxicology, economics, and management. The ultimate purpose of the coordinated effort is to assist water suppliers to provide a reliable supply of safe and affordable drinking water to consumers. The true benefits of the Foundation's research are realized when the results are implemented at the utility level. The Foundation's staff and Board of Trustees are pleased to offer this publication as a contribution toward that end.

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\* Richard Giani and Nicole Condon are no longer employed by DC Water. Mr. Giani is now Water Quality Manager for the Portland Water Bureau, and Ms. Condon is now Research Assistant in the EPA National Center for Environmental Economics.



## EXECUTIVE SUMMARY

### BACKGROUND AND OBJECTIVES

The efficacy of partial lead service line replacements (LSLRs) as a lead abatement measure has been debated since the early rule making of the EPA Lead and Copper Rule (LCR). Conflicting research on the subject has continued. In particular, this specific project was prompted by the apparently conflicting results in two prior research reports published in 2010 by the Water Research Foundation (WaterRF). One project, “Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2” (WaterRF Project #3107) concluded that galvanic corrosion was an issue but that the galvanic effects were transient and short-lived (Boyd, et al. 2010b). The second project, “Contribution of Galvanic Corrosion to Lead (Pb) in Water after Partial Lead Service Line Replacements” (WaterRF Project #4088b) also observed evidence of galvanic corrosion, but it further concluded that the effect can be substantial and long-term (Triantafyllidou and Edwards 2010).

The specific objectives for this project were:

- Provide an unbiased third-party review of the two referenced previous Water Research Foundation (WaterRF) reports on lead corrosion (#3107 and #4088b).
- Develop guidance for water utilities on strategies for minimizing lead release from partial LSLRs, on the basis of experiments conducted with commercially available transition couplings rather than simulated connections. This objective was pursued through implementation of two parallel experimental programs conducted using field harvested lead pipe and various types of transition couplings.
- Report on post replacement sampling conducted by two participating utilities as part of regularly specified sampling and special studies.
- Address additional data gaps regarding water quality and low-lead brass fittings relevant to identifying best practices for minimizing lead release associated with partial LSL replacements.

### LITERATURE REVIEW

The literature review for this project was particularly focused on the two previous contradictory WaterRF sponsored projects. In addition, the review covered other research contributions on the subject that had been published up to the date of the writing of the review (February, 2012).

The WaterRF projects that were the focus on this review yielded important findings regarding lead release following galvanic and non-galvanic corrosion. The projects had different objectives and consequently followed different research approaches. The most significant differences in approaches that could have influenced the results were:

- **Different Stagnation and Flow Regimes.** The continuously recirculating flow in Project #3107 (“*Changing Disinfectants*”) is ideal for the development of passivating pipe scales that could limit lead release associated with galvanic corrosion; this would be an optimistic best case scenario. In contrast, the dump-and-fill mode used in Project #4088b (“*Galvanic Corrosion*”) presented a worst case scenario for lead release due to

local low pH regions, insufficient time and new water to promote scale development, and long stagnation times.

- **Different Measurements of Lead Release.** The collection of samples from the recirculating reservoir of Project #3107 (*“Changing Disinfectants”*) did not allow measurement of all of the lead released from the pipes, so these measurements represent lower bounds on the total lead released. Project #4088b (*“Galvanic Corrosion”*) did measure all of the lead released.
- **Different Lead Pipe Materials.** Neither project used harvested aged pipes that would be most representative of those involved in actual partial LSL replacements. Starting with new lead pipe makes the issues of scale development all the more important.
- **Different Water Chemistry.** Because each project studied waters with different compositions, differences are to be expected. Perhaps most significantly, Project #3107 (*“Changing Disinfectants”*) employed periods of free chlorine that promote the development of  $\text{PbO}_2$ , which can be very effective in limiting galvanic corrosion and lead release; Project #4088b (*“Galvanic Corrosion”*) used monochloramine, which would not have been capable of oxidizing lead to the +IV oxidation state to yield  $\text{PbO}_2$ .

## EXPERIMENTS CONDUCTED IN THIS PROJECT

Two parallel sets of experiments were conducted in this project: (a) a series of short-term (six-week) experiments conducted at laboratory scale, and (b) a set of longer term experiments (up to a year duration in some cases) conducted at pilot scale.

### Laboratory Scale Experiments

The experiments were conducted using used lead pipe which had been excavated from service lines in Providence, RI, and Washington, DC. The experiments examined the difference in lead release when new copper tubing is connected to lead pipe using four different types of commercial connectors, all designed for buried application: (a) standard brass compression coupling, (b) brass dielectric coupling, (c) plastic coupling, and (d) low-lead brass compression coupling. The experiments were conducted using recirculating loops (with samples drawn from the pipe assembly, and not the recirculation reservoir) and used simulated water chemistries designed to be representative of the two systems from which the test pipes were taken. Selected changes in water chemistry were also examined. Principal observations from the lab experiments included the following:

- **Differences by type of coupling** - Under the conditions of the lab scale experiments there were clear differences in lead release among the types of couplings used. The pipe assemblies with the plastic couplings always had the lowest lead release and those with the standard brass couplings the highest lead release.
- **Rate of lead release over time** - For most of the experiments there was not a significant change in the amount of lead released as a function of time over the six week duration.
- **Distribution of released lead between dissolved and particulate** - For the plastic coupled systems most of the lead released was in dissolved form, while for all of the brass-coupled systems particulate lead was the dominant form contributing to total lead measurements. Particulate lead may be the main source of lead release due to galvanic reaction between lead and copper.



- **Stagnation time effect** - For the brass coupled assemblies, samples taken after a 65-hour stagnation time (i.e. after the weekend) had much higher particulate lead concentrations than samples taken after six hours stagnation (i.e., consistent with LCR sampling).
- **Effect of Water Chemistry** – For water with the composition of the Washington, DC distribution system, increasing the chloride-to-sulfate-mass ratio from its original value of 0.7 to a value of 7.0 had no effect on lead release. For the Providence water, the addition of orthophosphate decreased the overall lead release to solution, even at relatively high pH.

## Pilot Scale Experiments

A series of pilot scale experiments were conducted at the Fort Reno Water Quality Office of DC Water. These pilot scale experiments were conducted on excavated lead pipe from Washington, DC, with ambient water from the distribution system. Water was run through the pipe assemblies on a timed basis with short 3-minute flows alternating with 8-hour stagnation periods, in a once-through flow regime. The sampling flow rates for the Fort Reno experiments were considerably higher than that used in the laboratory experiments (2.65 gpm vs 0.26 gpm). The Fort Reno sampling flow rates were set at what was judged to be the high end of typical kitchen faucet flows.

The Fort Reno pilot scale experiments exhibited much “noisier” data than was experienced in the lab scale experiments. Although there was some differentiation between the coupling types, it was much less than the variability between pipe assemblies considered to be duplicates. Because of this it is not possible to say with confidence that any of the tested coupling types was superior in terms of reducing lead release following a partial LSLR. Generally, the experiments showed an increase in lead release following the connection of the copper tubing to the conditioned lead pipe for all the coupling types, suggesting that even the plastic and the brass dielectric do not totally suppress lead release. In these experiments the lead concentrations declined over time, until reaching similar stable values after two to three months for all tested types of transition couplings.

## REVIEW OF FIELD DATA FOR PARTIAL LSLRs

Both of the participating utilities, DC Water and Providence Water, were engaged in extensive LSLR programs preceding and during the course of this study and shared data that were collected from these programs. These data included both post-partial LSLR data that were collected routinely pursuant to the Lead and Copper Rule and data collected in special surveys. These data tracked programmed replacements that were done using standard brass transition couplings to join the new copper tubing to existing lead pipe.

The post-partial sampling conducted in the DC Water system in 2006 included both first-draw samples (i.e. taken immediately upon water draw, consistent with prescribed LCR sampling protocols) and “second draw” samples (taken after a sensed change in water temperature, indicative of water from the buried service line). In an analysis of the 90<sup>th</sup> percentile statistics for the 2006 post-partial data set, it was found that lead was significantly elevated immediately after the pipe replacement event. This was followed by a clear reduction over time in which it was four to six months before both the first and second draw data were consistently below the 15 µg/L LCR Action Level. In a subsequent special study conducted by DC Water in 2010

sampling households with both full and partial LSLRs (13 and 16, respectively), it was found that all tested below the LCR Action Level after 4.5 months.

Comparable results are documented for two special studies conducted in Providence, RI. Providence Water's conducted an investigation which followed 21 households with partial LSLRs over time, finding that a drop in first-draw sample concentrations to the 15 µg/L level for the 90<sup>th</sup> percentile statistic occurred approximately 90 days after replacement. In a separate study conducted by the Rhode Island Dept of Health of eight households with partial LSLRs, there was an immediate rise in first-draw lead concentration for most homes following the replacement, and in all cases concentrations dropped below 15 µg/L by the end of four months.

## OVERALL FINDING

This project was initiated in an attempt to resolve apparently contradictory conclusions reached between two previous WaterRF projects. One project, #3709 (*Changing Disinfectants*) concluded that galvanic corrosion was an issue but that the galvanic effects were transient and short-lived (Boyd, et al. 2010b). The second project, #4088b (*Galvanic Corrosion*) also observed evidence of galvanic corrosion, but it further concluded that the effect can be substantial and long-term (Triantafyllidou and Edwards 2010).

In the paragraphs above we summarize our comparative critique of the experimental approaches and findings of the two projects. Our literature review, performance of new experiments, and review of field data from two large lead service line replacement programs offers new information regarding the magnitude and duration of elevated lead concentrations following partial LSLR. The laboratory experiments, conducted for a six week period, indicate that galvanic corrosion can cause statistically significant increases in lead concentrations. The extended timeframe pilot experiments (16 to 57 week durations) also had elevated lead concentrations following connections of lead pipe to copper tubing, but the findings were not conclusive as to how much of this increase is attributable to galvanic mechanisms.

Regarding the duration of elevated lead concentrations, field observations from two large LSLR programs summarized in this report suggest that elevated concentrations may abate in a time period of four to six months. It should be noted that these field post-partial-LSLR samples were likely not collected at consistent flow rates since the sampling guidance followed that specified in the LCR, which does not specify a sampling water flow rate, and the residents collected the samples. As we have observed in our research and has been reported by other researchers, the flow rate can affect lead release rates. This project's longer term pilot experiments, which were conducted with sample flow rates similar to or somewhat greater than typical kitchen faucet use, exhibited concentrations that declined to stable lower values after durations that ranged from about four months to ten months.

## RECOMMENDATIONS

Overall conclusions of direct import to utilities dealing with lead abatement from lead service lines are:

- Lead release via galvanic corrosion was clearly evident under the conditions of the lab scale experiments, and to a more limited extent in the pilot scale experiments. For the tests in which there was good replication of data, the non-conductive plastic couplings always released less lead than the conductive metal couplings. Consideration should be

given to use of non-conductive couplings where partial LSLRs must be undertaken. If a decision is made to use plastic couplings for the purpose of abating galvanic corrosion effects, it is recommended that a plastic spacer be inserted in the center of the assembly to assure that there is no contact between the two pipes.

- If a water utility should wish to mitigate adverse galvanic effect through use of a dielectric or plastic coupling, consideration will have to be given to alternative means of grounding the household electrical wiring system. If a partial service line replacement would result in less than ten feet of buried metal pipe in contact with the earth, than an alternative method of grounding would have to be provided for the electrical system to remain code compliant. In many cities with older lead service lines, a substantial percentage of the service lines would fall into this category. Further background is given in Appendix E.
- The longer term pilot scale experiments were supportive of field observations of actual partial LSLRs that elevated lead release following a replacement does abate over time. In the field data the concentrations fell below the LCR Action Level of 15 µg/L within four to six months.

In view of the elevated lead release that was found to be typical following partial LSLRs, utilities will have to use other mitigation measures to abate lead release following service line replacement. Measures that have been found suitable and have been adopted by both the participating utilities in this study (DC Water and Providence Water) consist of the following:

- Enhanced customer outreach and education - The Lead and Copper Rule contains prescribed language that must be used in required customer outreach regarding lead following LCR Action Level contraventions, and this must absolutely be followed. However, an appropriately aggressive outreach program can go beyond the required language in terms of the number of times that the customer is contacted both before a planned replacement, and afterwards (regardless of whether the replacement is a planned or emergency repair action.)
- Enhanced flushing - The service line should be thoroughly flushed by the utility on the day of the event, and the customer should be instructed to thoroughly flush the plumbing daily for a period of time after. The protocol of DC Water entails 60 minutes of flushing on the day of the replacement by the work crew, supplemented by outreach instructions to the customer to flush the system at a vigorous flow rate for ten minutes daily for the next thirty days. Customers are also sent reminder postcards for four weeks following the replacement reminding them of the ten-minute daily flush, as well as a two-minute flush whenever the water has not been run for a period of six hours.
- Alternative water supply provision - Both DC Water and Providence Water have adopted the practice of providing the customer with a water filter, generally a pitcher style filter, that is certified for lead removal under the NSF/ANSI Standard 53 for lead reduction, along with sufficient replacement filter cartridges for a six month period of normal use. DC Water supplements this with the practice of providing for a follow-up lead analysis 4.5 months after the replacement to confirm that the lead content is below the LCR Action Level, and to inspect the premises for explanation if the lead is found to be still elevated.



# CHAPTER 1: INTRODUCTION

## BACKGROUND

The existence of lead service lines in many older cities in North America and in Europe has been a particularly intractable problem for water utilities due to the recognized health hazard of leached lead into the water, and because of the complications of the usually mixed responsibility of ownership and control between the utility and the customer.

The health hazard related to lead pipe was recognized as early as the first century. Vitruvius (Hodge 1981) wrote in the eighth volume of his ten volume treatise “De Architectura” that:

"Water conducted through earthen pipes is more wholesome than that through lead; indeed that conveyed in lead must be injurious, because from it white lead [*cerussa*, cerussite or lead carbonate,  $PbCO_3$ ] is obtained, and this is said to be injurious to the human system. Hence, if what is generated from it is pernicious, there can be no doubt that itself cannot be a wholesome body. This may be verified by observing the workers in lead, who are of a pallid colour; for in casting lead, the fumes from it fixing on the different members, and daily burning them, destroy the vigour of the blood; water should therefore on no account be conducted in leaden pipes if we are desirous that it should be wholesome." (VIII 6.10-11)

When the major water utilities in North America were being established in the early twentieth century, there was some recognition of the potential health hazard of conveying water in lead pipes; however, lead pipe was also regarded as having particularly desirable mechanical characteristics, particularly in comparison with other alternatives available for service pipe use. These apparently contradictory assessments are evident in the following two quotations from the New England Water Works Association's 1917 report of its committee on service pipes.

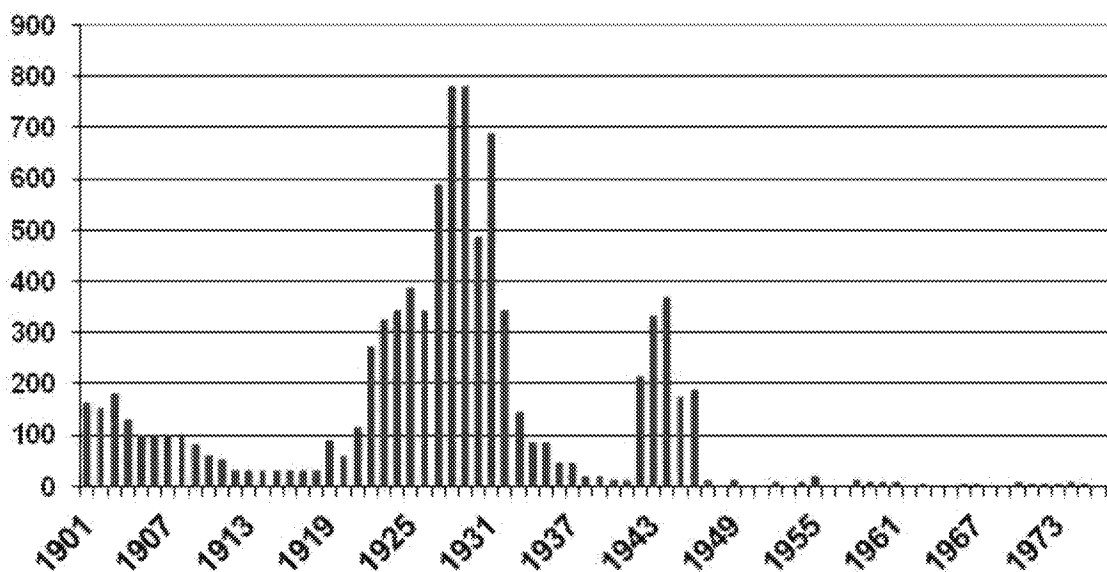
“Hippocrates recognized the danger of lead poisoning in connection with water supplies, and the fact that water conveyed through lead pipes or held in lead cisterns sometimes became poisonous was commented upon by medical writers of the middle ages.” (NEWWA 1917, pg 333).

“Lead is in many respects the most satisfactory material to use for service pipes. Its pliability and its comparative freedom from corrosive action make it almost ideal from a mechanical standpoint. The cost of lead pipe of sufficient thickness to safely withstand the pressure is more than the cost of many other materials used for services, but in a paved street the greater duration of life probably more than compensates for the extra cost, and in places where the streets are occupied by other pipes and conduits the ease of getting over and under these obstructions with a flexible pipe is a great advantage.” (NEWWA 1917, pg 336).

A considerably less sanguine perspective on the contemporaneous health effects of the early utility use of lead pipe has been documented by Troesken (2003, 2006) and Troesken and Beeson (2003). Rabin (2008) provides a review of the industry and political actions that were in play to maintain lead pipe as a widely used product despite misgivings over its health effects.

Lead pipe was widely used in service line installations by a number of water utilities. The 1917 NEWWA service line committee surveyed 304 utilities, primarily in New England, and found that 99 reported that their practice was to use lead pipe or lead-lined iron pipe for customer services (NEWWA 1917). Some 65 years later the EPA conducted a nationwide survey of 153 utilities in which 73% reported known inventories of lead service lines, and 62% reported past practice of having used lead “goose necks” as flexible connectors between other service line materials and the water main pipes. At the time of the 1984 survey, there was still one major city that still listed lead as an acceptable service line material in its system (EPA 1985).

In typical industry practice lead pipe remained a dominant service line material until it was largely supplanted by what was considered a superior product, copper tubing. The use of lead pipe was totally discontinued when prohibited nationally in 1986 under the Safe Drinking Water Act. The historical use of lead pipe in Washington, DC, depicted in Figure 1.1, may be typical of many large cities whose water systems largely developed in the first half of the twentieth century.



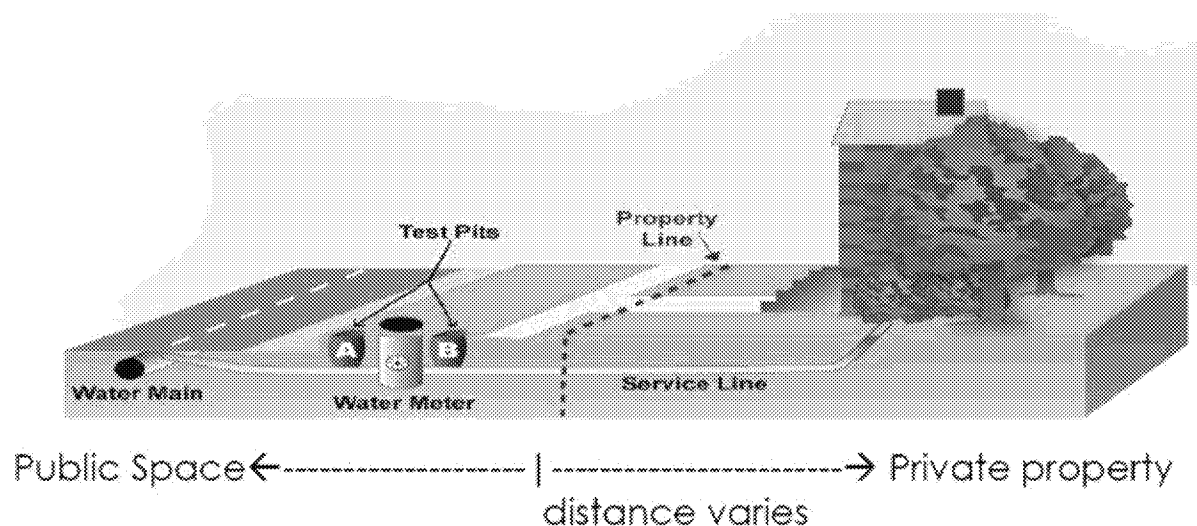
Source: Weston, 1990

**Figure 1.1 Recorded lead service line installations in the District of Columbia**

The properties that made lead pipe attractive originally, particularly its physical durability and the fact that it does not build up a hydraulically obstructive internal scale, means that it seldom requires replacement because it no longer is able to convey water. Thus these lead service lines are now an enduring legacy infrastructure remaining in many large cities. The health hazard it represents was a significant impetus for the Environmental Protection Agency to enact the Lead and Copper Rule (LCR) in 1991 (subsequently amended in 2000, 2004 and 2007). The LCR requires water utilities to manage the water chemistry of their finished water to minimize its tendency to leach lead and copper from the customer’s plumbing system, including the service lines and internal plumbing. To monitor their success in this objective, utilities are

required to sample the water from a representative number of customer kitchen taps to confirm that the water at the tap is below the LCR Action Level for both lead and copper. The Action Level for lead is established in the rule such that 90 percent of the samples must be below 15  $\mu\text{g/L}$ . If this concentration is exceeded during the regulatory monitoring period, the utility is required to undertake a number of prescribed response measures until the corrosivity of the water is reduced and the 90<sup>th</sup> percentile value for monitoring falls below 15  $\mu\text{g/L}$ . The most rigorous of the response measures required is that the utility implement a program to replace lead service lines that it controls in the distribution system at a rate of 7% per year.

Complicating this requirement is that in most cases the water utility does not own the entire service line. Typically the service line is by local law a shared asset, with the utility controlling its length from the water main to some defined midpoint (typically, the property line, the curb line or curb stop, depending on local custom or law). The customer owns the remaining segment of the line to the house. An illustration of this division is in Figure 1.2, in this case based on the property line, which is the point of demarcation in Washington, DC. Under the LCR the utility is required to conduct outreach education with the customer on the nature of the health hazard of the lead pipe, and to facilitate coordinated voluntary replacement of both portions of the lead service line. However, in most cases utilities find that customers do not choose to participate in their part of service line replacement. Customer participation rates in lead service line replacements are reported to range from approximately 1% to 25%, largely influenced by the cost of the operation. The resulting replacement of only the public portion of the service line is termed a partial lead service line replacement (LSLR) or (PLSLR).



Source: DC Water (various public outreach documents)

**Figure 1.2 Typical public/private demarcation of water service line**

The section of lead pipe removed in a PLSLR is most frequently replaced with new copper tubing. If the lead pipe and copper tubing are connected using an electrically conductive material, such as a brass coupling, then the connection makes it possible for galvanic corrosion to occur. Galvanic corrosion can occur when two dissimilar metals are electrically connected and are in contact with the same aqueous solution. The different electrochemical properties of the metals can result in one of them (the anode) corroding faster than it would if it were present

in isolation. For lead and copper connections, lead acts as the anode and consequently PLSLRs may exacerbate lead release to water. Galvanic corrosion and associated previous research are extensively reviewed in Chapter 2.

Most partial LSLRs are the result of LCR compliance activities. However, utilities with lead service line inventories also have to deal with this problem in operations incidental to programmed water infrastructure renewal construction projects or unplanned emergency repairs.

## **PROJECT GOALS**

The efficacy of partial LSLRs as a lead abatement measure has been debated since the early rule making of the LCR. In the preamble to the 2000 issuance of the LCR the EPA reviewed a number of contradictory scientific investigations, some of which had indicated reductions in lead-in-water concentrations following partial LSLRs, and some of which had documented increases in lead (Federal Register, 2000).

Conflicting research on the subject has continued. In particular, this specific project was prompted by the apparent conflicting results in two prior research reports published in 2010 by the Water Research Foundation (WaterRF). One project, “Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2” (WaterRF Project #3107) concluded that galvanic corrosion was an issue but that the galvanic effects were transient and short-lived (Boyd, et al. 2010b). The second project, “Contribution of Galvanic Corrosion to Lead (Pb) in Water after Partial Lead Service Line Replacements” (WaterRF Project #4088b) concluded that galvanic corrosion is an issue also, but that the effect can be substantial and long-term (Triantafyllidou and Edwards 2010).

The primary objective of the research project was to advance understanding of the potential effects of galvanic corrosion on lead release associated with partial lead service line replacements. Specific objectives were to:

- Provide an unbiased third-party review of previous Water Research Foundation (WaterRF) reports on lead corrosion.
- Develop guidance for water utilities on strategies for minimizing lead release from partial LSLRs, on the basis of experiments conducted with commercially available transition couplings rather than simulated connections. This objective was pursued through implementation of two parallel experimental programs conducted using field harvested lead pipe and various types of transition couplings.
- Report on post replacement sampling conducted by two participating utilities as part of regularly specified sampling and special studies.
- Address additional data gaps regarding water quality and low-lead brass fittings relevant to identifying best practices for minimizing lead release associated with partial LSL replacements.

## **OUTLINE OF THIS REPORT**

This report documents the research conducted for this project, including a focused literature review (focused primarily on the two apparently conflicting prior WaterRF projects), two sets of experiments conducted to simulate partial LSLRs, and a review of field data collected



by two participating utilities that have conducted extensive LSLR programs pursuant to the Lead and Copper Rule.

Chapter 2 is the review of the literature on the mechanism of galvanic corrosion as a contributor to lead release following a partial LSLR. This chapter specifically focuses on the two conflicting research efforts that prompted this study, and its objective is to provide an unbiased third-party review. The research teams that authored both of the two principal reports have also continued their research in this area, and this review covers some of their later reporting. (The comparative review of the prior conflicting research reports is covered only in Chapter 2. The other chapters in this report cover new experiments conducted under this project, except Chapter 6, which is a synthesis of field data that has been collected during the lead service replacement programs in Washington, DC, and Providence, RI.)

Chapter 3 covers a set of bench-scale experiments conducted at the Washington University in St. Louis (WUSTL). These experiments used harvested lead pipe segments that had been exhumed from the ground (in Washington DC and Providence RI), which is in contrast to most prior research experiments which have been conducted on virgin lead pipe. These experiments also used commercially available couplings, another contrast with most prior research in which laboratory tubing connections were typically employed. The WUSTL experiments were conducted in a laboratory setting with recirculating pipe loops, and were typically of six-week duration. A number of experiments were conducted using variations in the chemistry of the challenge water, as well as the coupling variation.

Chapter 4 describes a parallel set of pilot-scale experiments which were conducted by staff of the DC Water and Sewer Authority (DC Water) at the Fort Reno Water Quality Office. Similar to the WUSTL experiments, the Fort Reno experiments utilize harvested lead pipe (from Washington DC) and the four types of commercially available transition couplings: a typical brass compression coupling, a brass coupling with an internal nylon dielectric bushing, an all-plastic coupling, and a standard brass compression coupling with low-lead brass content. The Fort Reno experiments were run for a longer duration, on a flow-to-waste basis (rather than a recirculating flow) using treated water from the DC distribution system.

Chapter 5 is a comparative synthesis of WUSTL and Fort Reno experiments, comparing methods used and results obtained.

Chapter 6 consists of a review of sampling data obtained by the two participating utilities (DC Water and Providence Water) in the course of the large LSLR programs that both utilities have undertaken pursuant to LCR compliance. These data include post-partial LSLR sampling that the utilities did as required under the LCR, and special sampling projects that both utilities undertook to better understand the effectiveness of the LSLR operations.

The discussion continues in Chapters 7 and 8 along with overall conclusions and recommendations to utilities.



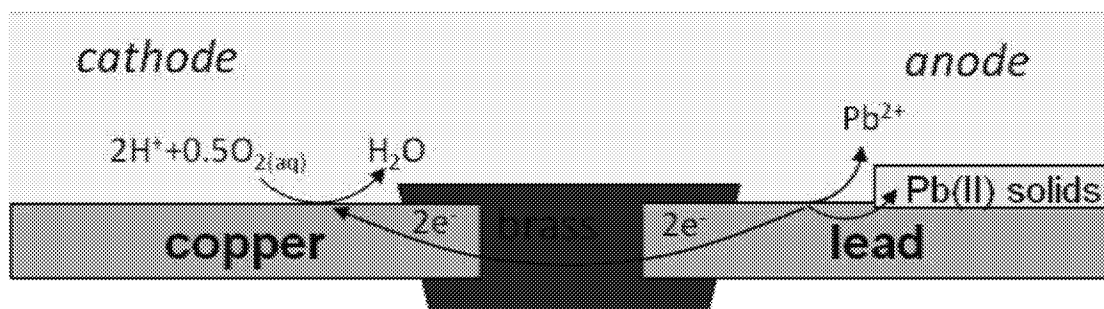
## CHAPTER 2: REVIEW OF PREVIOUS WATER RESEARCH FOUNDATION PROJECTS ON GALVANIC CORROSION

### OVERVIEW OF GALVANIC CORROSION

The general process of corrosion involves the chemical oxidation of a metal from one oxidation state to a higher oxidation state. The oxidation of lead metal (i.e. the 0 oxidation state) that makes up the original lead pipe is oxidized to forms of lead in the +II oxidation state. If high concentrations of free chlorine are maintained, then lead in the +IV oxidation state can also be produced. The oxidants for corrosion processes include dissolved oxygen and oxidized forms of chlorine (hypochlorite and hypochlorous acid in particular) used in disinfection (Schock and Lytle 2011).

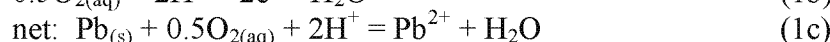
Forms of lead(II) produced by corrosion include both dissolved lead species (e.g.,  $\text{Pb}^{2+}$  and soluble complexes with hydroxide and carbonate) and solid phases. Depending on the specific water chemistry, the lead(II)-containing solid phases can be oxides (e.g.,  $\text{PbO}$ ), carbonates (e.g.,  $\text{PbCO}_{3(s)}$ ), hydroxycarbonates (e.g.,  $\text{Pb}_3(\text{CO}_3)_2(\text{OH})_{2(s)}$ ), and phosphates (e.g.,  $\text{Pb}_5(\text{PO}_4)_3\text{OH}_{(s)}$ ) (Schock and Lytle 2011). Over time a pipe scale that contains the solid corrosion products develops on the surface of the lead pipe. The dissolved lead concentration in the water can then be controlled by the solubility and dissolution rates of these corrosion products and not by the rate of corrosion of the underlying lead metal. In addition to the release of dissolved lead, lead in suspended particulate and colloidal forms can be released from the pipe surfaces (Deshommes et al. 2010). Further, the development of the scale can block the access of oxidants to the lead metal surface and slow down the rate of lead metal corrosion, a process known as passivation (MWH 2005).

Galvanic corrosion is a particular type of corrosion that involves accelerated oxidation of one metal as a result of forming an electrical connection with a different metal. The driving force for corrosion involves the differences in the electrochemical potential of the two different metals (MWH 2005). The process is the same one involved in generating electricity from batteries. The connection of the two different metals creates a galvanic cell. In this cell the metal with the lower electrochemical potential is oxidized. This oxidation introduces electrons into the electrically conductive pathway of the connection of the two metals (either through direct contact or through another conductive pathway such as a metal coupling) where they travel to the metal with the higher electrochemical potential to participate in the chemical reduction of a species in solution. In an electrochemical cell, the metal that is being oxidized is the anode and the metal on which the chemical reduction process occurs is the cathode. Because the reactions at both metal surfaces either generate or consume charged species, the water within the pipe serves the essential role of allowing for ionic transport from the anode and cathode and maintenance of overall charge balance. All other factors being equal, galvanic corrosion is higher for solutions with higher conductivity (i.e., higher ionic strength or total dissolved solids). Without both the ability of solute transport through the water and of electron transport through the metals, galvanic corrosion cannot occur.



**Figure 2.1 Process of galvanic corrosion occurring upon the electrical connection of lead and copper in water. The connection as shown has electron conduction through a brass fitting, and conduction can also proceed through direct copper-lead contact or through external wires that connect lead and copper sections.**

The process of galvanic corrosion is illustrated for the case of a connection of lead and copper with the oxidation of lead metal to soluble  $\text{Pb}^{2+}$  being coupled with the chemical reduction of dissolved oxygen on the copper surface (Figure 2.1). The galvanic connection can be through direct contact of the copper and lead or through a conductive material like the brass fitting shown in Figure 2.1. The net reaction involves the consumption of  $\text{H}^+$  (i.e., acid), which can cause the overall pH to increase, but the increase of pH will be spatially localized on the copper and gradients in pH and the dissolved lead concentration will develop in the water for a galvanic connection.



Just as the pH increase is localized on the copper cathode, a corresponding localized pH decrease can occur on the lead anode. The free lead ion ( $\text{Pb}^{2+}$ ) is a Lewis acid, which means that its formation of complexes with  $\text{OH}^-$  can generate acidity (i.e., release of  $\text{H}^+$ ) (Stumm and Morgan 1996).



If lead release is localized to a particular spot on the lead pipe surface, then the pH can decrease considerably. The extent of the pH decrease will depend on the alkalinity of the water, the rate of corrosion, and the rates of convective and diffusive transport of solutes away from the area of localized lead release. Galvanic corrosion can potentially involve a positive feedback through which the generation of a low pH zone on the lead surface further accelerates the corrosion reaction (Nguyen et al. 2010).

Galvanic corrosion is relevant to partial lead service line (LSL) replacements in which a portion of an old LSL is removed and then replaced with a new copper pipe. If the coupling between the old lead pipe and the new copper pipe is conductive, as is the case with commonly used brass fittings for making the connection, then galvanic corrosion will occur.

At the time of most lead service line installations, galvanized iron was the primary material used for premise plumbing. The electrochemical potential of iron is such that it would corrode preferentially to lead and act as an anode that may actually protect the lead from corrosion, and the iron itself for galvanized iron is further protected by zinc acting as the anode (MWH 2005). Subsequent modifications of plumbing in most houses have replaced the galvanized iron with copper, but many locations will have mixtures of copper and galvanized iron. For locations with a lead service line connected to copper premise plumbing, the lack of association of these connections with elevated lead release may simply be due to a lack of measurements of lead in tap water at the time of the original installation (often 100 years ago or more) and that the lead pipe passivated against further corrosion in the interceding decades.

This review has been prepared as part of the scope of work for Water Research Foundation (WaterRF) Project #4349. The objective of this task of the project is to provide an unbiased third-party review of two previous WaterRF reports on lead corrosion. One project, “Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2” (Project #3107), concluded that galvanic corrosion affects lead release but that the galvanic effects are transient and short-lived (Boyd et al. 2010b). The second project, “Contribution of Galvanic Corrosion to Lead (Pb) in Water after Partial Lead Service Line Replacements” (Project #4088b), which was part of a Project Continuation Reserve of an earlier project (Project #4088), it was reported that galvanic corrosion can be a substantial and long-term source of lead release (Triantafyllidou and Edwards 2010).

While the scope of this review is primarily focused on these two reports, in preparing this review we have found it helpful to also consider a chapter of the WaterRF report, Project #4088, “Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water”. Project #4088 was primarily focused on studying leaded solders and performing utility case studies (Nguyen et al. 2010), but Chapter 11 (“Utility H, WA – Pipe Loop Study”) included a pipe loop study that evaluated connections of lead pipe to copper tubing. This chapter describes a study done as part of a project led by the Project #4088b (*Galvanic Corrosion*) team but performed at a facility and by personnel of the Project #3107 (*Changing Disinfectants*) team. Chapter 11, which was prepared by Anne Sandvig and reviewed by Glen Boyd, presented the results of experiments that addressed galvanic corrosion issues between lead and copper pipe. The chapter’s description of the experimental methods provides helpful elaboration on those used in Project #3107. Therefore this report, #4088-Chapter 11, is addressed as a separate review in addition to those of Projects #3107 (*Changing Disinfectants*) and #4088b (*Galvanic Corrosion*).

The research groups that conducted the work in Reports #3107 and #4088b have continued research in this area, and some newer results from these groups are included in this review. Several additional references from studies conducted by other groups are also included.

## OVERVIEW OF WATERRF PROJECTS #3107, #4088 (CHAPTER 11), AND #4088B

Neither Project #3107 nor Project #4088 initially set out to investigate effects of galvanic corrosion associated with partial LSL replacement. Both were initially focused primarily on aspects of water chemistry on lead corrosion processes. The stated objective of Project #3107 (*Changing Disinfectants*) was “to ascertain effects of changing disinfectants from free chlorine to chloramines and vice versa on release of copper and lead from corroding lead, brass, and copper distribution system components.” The stated objective of Project #4088 was to

“determine the effects of chloride-sulfate mass ratio (CSMR) on lead leaching to potable water” (Nguyen et al. 2010). Results of this original project motivated the follow-up Project Continuation Reserve (PCR) study (Project #4088b), which included as one of three objectives “rigorously testing the longevity of galvanic corrosion with respect to lead contamination of drinking water.” All three projects sought to answer important questions regarding processes that could affect lead concentrations in drinking water, and they yielded important results for the water supply community.

Projects #3107 and #4088b followed research approaches that were different in several significant ways. The study presented in Chapter 11 of Project #4088 combined different aspects of the two other projects. The research approaches are briefly summarized here and are then described in greater detail in following subsections devoted to each project. Key differences in the research approaches are highlighted in Table 2.1. Project #3107 (*Changing Disinfectants*) used a pipe loop apparatus with constant recirculation of tap water adjusted to different water chemistry. The project investigated the impacts of free chlorine and chloramines on lead and copper release to water for different water compositions, with each composition studied for three months in an overall testing program of 12 months. Measurements included grab sampling of the water in the recirculating loop several times each week and collection of coupons for morphological analyses of corrosion scales. Project #4088b (*Galvanic Corrosion*) used test rigs of copper pipe connected through an external connection to lead pipes in an apparatus that were exposed to two synthetic tap waters in a static “dump and fill” protocol that was operated for a total of 31 weeks. The external electrical connection allowed a means of (a) controlling whether or not the copper and lead pipes could participate in galvanic corrosion and (b) measuring the electrical current when the pipes were connected. Chapter 11 of Project #4088 serves as a link between Projects #3107 and #4088b. The method of connecting the lead and copper was through the same external connection approach of Project #4088b, and the contact of water with the pipes was provided using recirculating flow as was done in Project #3107, although periods of stagnation were included in most of the Chapter 11 tests. The other portions of Project #4088 used the “dump-and-fill” protocol to investigate lead release from connections of solder containing lead to copper.

All three projects had aspects of their experimental designs that do not allow a direct extension of their results to predict the effects of galvanic corrosion on lead release following partial LSL replacement.

- None of the projects connected copper and lead pipes using the types of couplings that are used in practice for actual LSL replacements.
- The majority of experiments in each project were performed with either new lead pipe or with aged lead pipe that had its surface cleaned; this is in contrast to the old lead pipes that can have considerable scales of corrosion products that are connected to new copper pipes in actual LSL replacements.
- The flow regimes of either stagnant “dump-and-fill” or complete recirculation are different from that of intermittent periods of once-through flow interrupted by varying durations of stagnation.
- The water chemistry was changed more frequently than what may be necessary to ascertain truly long-term effects.

The projects' experimental designs did have advantages and were reasonable for meeting the primary objectives of the projects. The connection methods facilitated ease of construction, avoided potential interferences from brass, and allowed for measurements of current. The new or cleaned lead pipes would have greater release and potentially be more consistent from pipe to pipe than harvested lead pipes, especially if harvested lead pipes are not reconditioned following cutting, removal, and shipping. The static "dump-and-fill" and recirculating flow regimes avoided the need for much larger volumes of water of controlled composition. Changing water chemistry was critical to meeting the primary objectives and without much longer project periods (and correspondingly larger budgets) could not have been done simultaneously with observing effects over longer time periods.

Projects #3107 and #4088b reached differing conclusions regarding the significance and duration of galvanic corrosion effects on lead release (Table 2.2). Ultimately, Project #3107 (*Changing Disinfectants*) concluded that galvanic corrosion was a transient effect that would not have a large impact on lead release for lead-copper connections and Project #4088b (*Galvanic Corrosion*) concluded that galvanic corrosion could result in significant lead release over much longer periods of time. Reaching different conclusions is not surprising given the different primary objectives of the two projects and the different research approaches. Chapter 11 of Project #4088, which used aspects of approaches of both of the other projects, ends with the statement that "clear conclusions about the effects of Pb:Cu galvanic connections on leaching of lead from pure lead pipe are not possible" based on the results generated for that study.

**Table 2.1**  
**Research approaches followed by Projects #3107, #4088 (Chapter 11), and #4088b**

<b>Aspect of Approach</b>	<b><u>Project #3107</u></b> <b><i>“Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2”</i></b>	<b><u>Project #4088 (Chapter 11)</u></b> <b><i>“Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water - Utility H, WA – Pipe Loop Study”</i></b>	<b><u>Project #4088b</u></b> <b><i>“Contribution of Galvanic Corrosion to Lead (Pb) in Water after Partial Lead Service Line Replacements”</i></b>
Lead pipes used for experiments with potential galvanic corrosion	<ul style="list-style-type: none"> <li>• Harvested lead pipe from Seattle that was abraded and polished to remove scales</li> <li>• New bronze</li> </ul>	<ul style="list-style-type: none"> <li>• Harvested lead pipe previously used in Project #3107 (“newer”)</li> <li>• Old lead pipe harvested from Seattle with no removal of scales (“older”)</li> </ul>	<ul style="list-style-type: none"> <li>• New lead pipe</li> <li>• New lead pipe previously used for 4 months (called “Old Pb pipe A”).</li> <li>• New lead pipe previously used in 1-year experiments (called “Old Pb pipe B”).</li> </ul> <p>All three were treated for 3 hours with pH 2.0 water.</p>
Method of connecting lead and copper pipes	End-to-end connection with copper-based solder to copper or bronze pipes	External wired connection of lead and copper pipes separated by an insulating spacer	External wired connection of lead and copper pipes separated by an insulating spacer
Replicate pipe assemblies	Single lead-copper and single lead-bronze assemblies	One experiment with newer lead pipe and one with older lead pipe	4 lead-copper assemblies with different ratios of lead to copper lengths
Flow regime	<ul style="list-style-type: none"> <li>• Continuous recirculation from 20-L reservoir at 0.5 gpm</li> <li>• Water in reservoirs replaced each week</li> </ul>	<ul style="list-style-type: none"> <li>• One test with continuous recirculation from 20-L reservoir at 0.5 gpm</li> <li>• Four tests with intermittent flow (5 minutes every 8 hours)</li> <li>• One test with intermittent stagnation (5 minutes stagnation every 8 hours)</li> <li>• Water replaced weekly</li> </ul>	<ul style="list-style-type: none"> <li>• Stagnant “dump-and-fill” protocol</li> <li>• Complete water changes three times per week.</li> </ul>

(continued)



Table 2.1 (Continued)

Aspect of Approach	<u>Project #3107</u> <i>“Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2”</i>	<u>Project #4088 (Chapter 11)</u> <i>“Impact of Chloride:Sulfate Mass Ratio (CSMR) Changes on Lead Leaching in Potable Water - Utility H, WA – Pipe Loop Study”</i>	<u>Project #4088b</u> <i>“Contribution of Galvanic Corrosion to Lead (Pb) in Water after Partial Lead Service Line Replacements”</i>
Water compositions	<ul style="list-style-type: none"> <li>• Local tap water for Seattle Public Utilities and for DC Water as base composition</li> <li>• Examined in 4 tests: (a) baseline, (b) alkalinity increase, (c) pH decrease, and (d) phosphate addition</li> <li>• For each test examined change in disinfectant from none to free chlorine, to monochloramine, and then back</li> </ul>	<ul style="list-style-type: none"> <li>• Local tap water for Seattle Public Utilities as base composition</li> <li>• Conducted three tests at a low chloride-sulfate-mass-ratio (CSMR) of 1-2 and three tests at a higher value of 8-12</li> </ul>	<ul style="list-style-type: none"> <li>• Synthetic tap water with low CSMR for 11 weeks.</li> <li>• Synthetic tap water with high CSMR for 14 weeks with galvanic connection and 6 weeks without galvanic connection</li> <li>• Both waters initially included 4 mg/L as Cl<sub>2</sub> chloramine</li> </ul>
Frequency of changing water composition	Minimum frequency of every two weeks	Changes water compositions or flow regimes	11 weeks before changing to new composition
Sampling frequency	<ul style="list-style-type: none"> <li>• Three grab samples per week for lead analysis</li> <li>• Daily monitoring and adjustment for pH and chlorine</li> </ul>	<ul style="list-style-type: none"> <li>• Three grab samples per week for lead analysis</li> <li>• Flowing reservoir samples</li> <li>• Mixed reservoir samples</li> <li>• Acidified reservoir samples</li> </ul>	One composite water sample per week from the three water changes
Lead measured	Total lead only	Total lead only	Total lead only
Electrical or electrochemical measurements	<ul style="list-style-type: none"> <li>• Open circuit potential</li> <li>• Polarization resistance</li> </ul>	Current through the external electrical connection	Current through the external electrical connection
Analysis of pipe scales	Coupons collected for electron microscopy and spectroscopy	Not performed	Not performed

**Table 2.2**  
**Summary of conclusions excerpted from Projects #3107 and #4088b<sup>1</sup>**

<b>Project #3107 (<i>Changing Disinfectants</i>)</b>	<b>Project #4088b (<i>Galvanic Corrosion</i>)</b>
Galvanic effects appear to be very sensitive to initial chlorine/chloramines (or vice versa) transitions.	High sustained galvanic currents between copper and lead pipe were measured when the CSMR (chloride:sulfate mass ratio) was high, resulting in galvanic corrosion of the lead. When the CSMR was low, galvanic corrosion still occurred but the galvanic currents were lower.
The effect is highly transient. Under steady state conditions, the shock of initial exposure quickly wanes.	The galvanic connection of copper to the lead materials evaluated in the study significantly increased lead leaching when compared to the situation when there was no electrical connection to copper pipe.
The area of influence of galvanic effects is limited.	Based on galvanic current measurements, the area of lead pipe adjacent to the copper join (< 0.5 ft) is most affected by galvanic corrosion.
In general, disinfectant conversion does not appear to have long-term significant impact on galvanic effects. However, background water quality conditions or particular mineral passivating scales that were not explored in this investigation may produce different results.	Galvanic connections between copper pipe and lead pipe (either new or old) could dramatically increase lead release compared to lead pipe alone, under stagnant water conditions.

<sup>1</sup> Chapter 11 of Project #4088 did not reach any clear conclusions regarding galvanic corrosion of lead pipes connected to copper.

## REVIEW OF REPORT #3107 (*CHANGING DISINFECTANTS*) SECTIONS RELATED TO GALVANIC CORROSION AND ASSOCIATED WORK

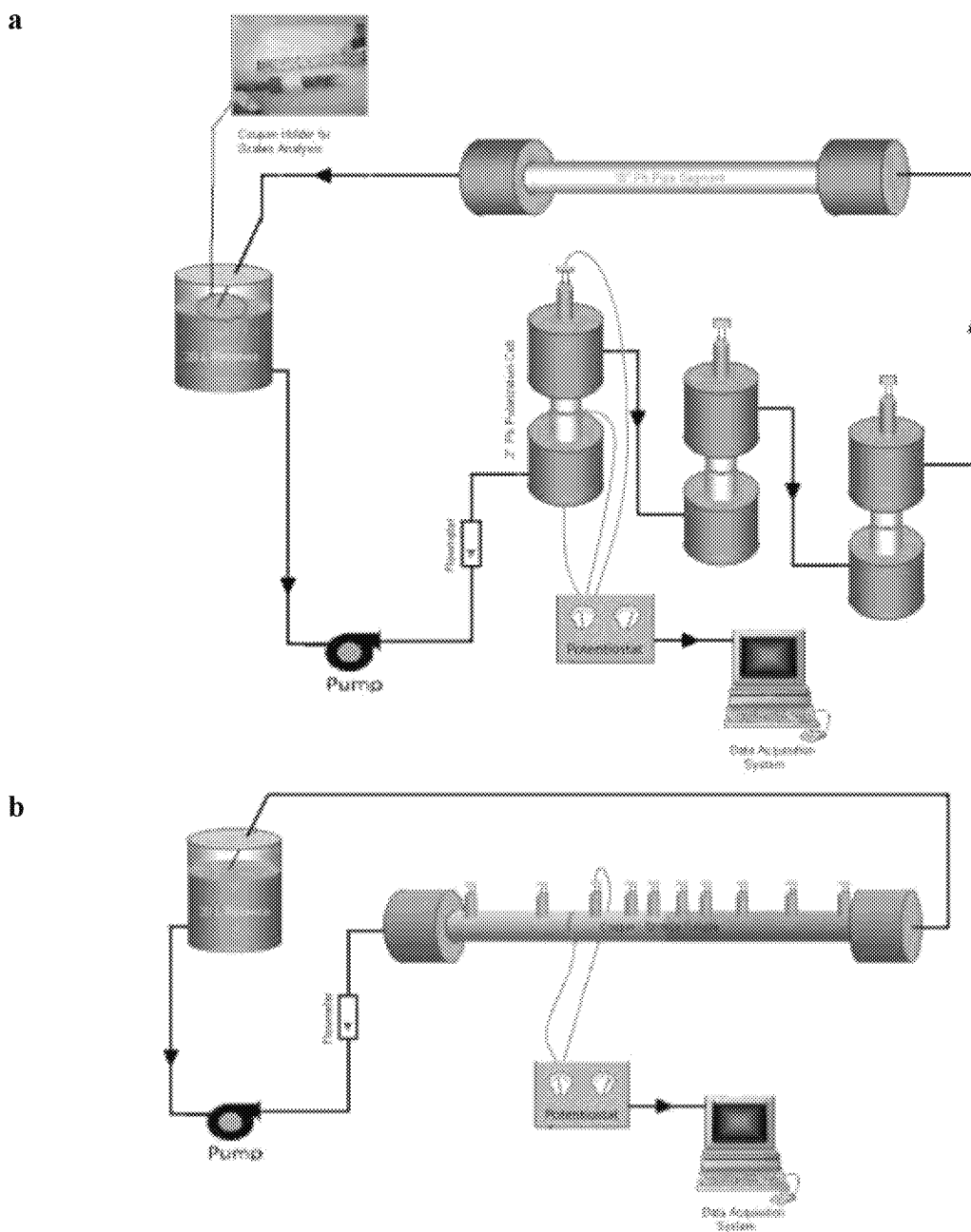
Project #3107 (“Effect of Changing Disinfectants on Distribution System Lead and Copper Release, Part 2”) employed recirculating pipe loop systems to examine the impacts of changing from chlorine to chloramines on lead and copper release for four different water compositions. Experiments were performed at both HDR’s Advanced Research and Technology Center (ARTC) facility in Redmond, Washington and at a District of Columbia Water and Sewer Authority (DC Water) testing facility in Washington, D.C. The results of experiments performed at the ARTC have resulted in the most subsequent presentations and publications and have an aspect of overlap with Project #4088, so this review will focus primarily on those experiments with limited discussion of the experiments at the DC Water facility. Experiments at both facilities compared the behavior of single lead pipes to those of lead pipes that were directly connected to copper or bronze pipes. Based on the work of this study, the research team conducted additional experiments on the effect of the type of copper-lead connection on electrochemical potentials (Boyd et al. 2010a; Boyd et al. 2012). While this follow-up work was done outside of Project #3107, its relevance to the initial study warrants its inclusion here.

### Summary of Experimental Approach – #3107 (*Changing Disinfectants*)

#### *Pipe Loops*

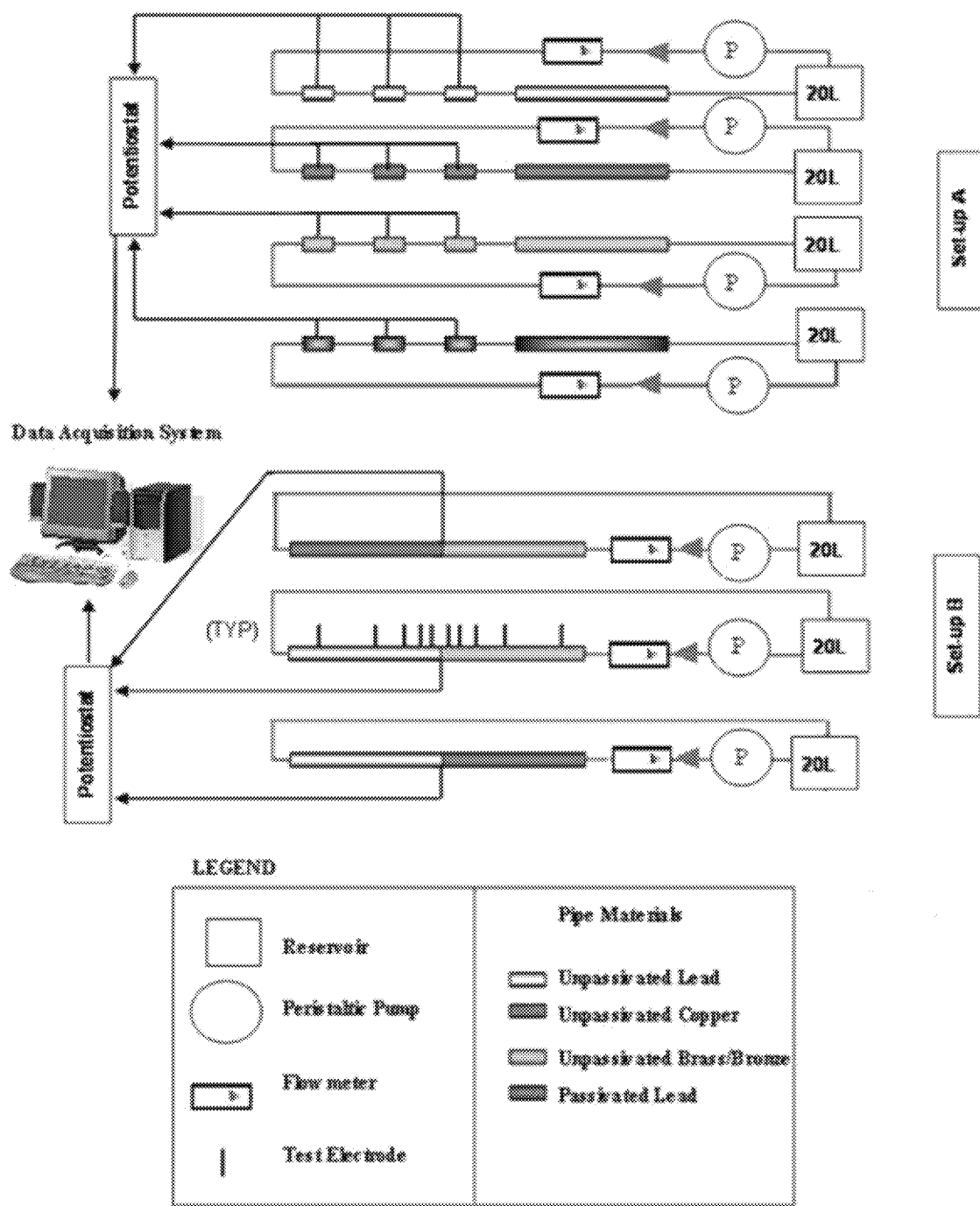
The galvanically-coupled pipe loops included an 18-inch lead pipe connected to either a new copper or a new bronze pipe (Figure 2.2) (Boyd et al. 2007). The lead pipes had been harvested from the Seattle Public Utilities service area and reamed prior to use so that their initial surfaces were those of unpassivated lead. Each dual-metal pipe loop received continuously recirculating water at a flow rate of 0.5 gpm from a 20-L dedicated reservoir. The pipes had multiple 5/8-inch holes drilled at varying distances from the connection of the two pipes to serve as electrode ports for electrochemical measurements. Each pipe loop also included penny-sized metal coupons in the recirculating flow path, but not connected to the pipes, that were used for analysis of scales. The surface areas of these coupons were much smaller than the surface area of the pipe walls so that their contributions to lead and copper concentrations were likely negligible. The overall layout of all single-metal and dual-metal pipe loops is presented in Figure 2.3. Pipe loop experiments at the DC Water facility had similar configurations. The single metal experiments at the DC Water facility used both old lead pipes that had their interior surfaces reamed to expose a fresh lead surface as well as two old lead pipes that did not have their scales removed.

The water chemistry was frequently changed in these experiments. The baseline for the tests at the ARTC was dechlorinated water from the Seattle Public Utilities distribution system. Experiments were performed in a series of four tests. In each test the water composition was altered every two weeks (three weeks in a few cases) in a sequence that evaluated the addition and removal of free chlorine and chloramines as disinfectants. The sequence progressed from (a) baseline, (b) non-chlorine change in water chemistry, (c) addition of 1.5 mg/L  $\text{Cl}_2$  free chlorine, (d) addition of 3.5 mg/L  $\text{Cl}_2$  monochloramine, (e) addition of 1.5 mg/L  $\text{Cl}_2$  free chlorine, (f) no disinfectant addition, and finally back to (g) the baseline prior to the non-chlorine change in water chemistry. After the first 3-month test examined the impact of disinfectants for



**Figure 2.2 Schematics of the (a) single-metal and (b) galvanic-coupled pipe loop setups used in Project #3107 (Originally Figures 3.1 and 3.2 of Project #3107, which were originally published in Boyd et al., 2007)**

the baseline water chemistry, three additional 3-month tests examined three changes to the baseline water chemistry (the change noted in step (b) above). These changes were increasing alkalinity from 20 to 140 mg/L  $\text{CaCO}_3$  (Test 2), lowering the pH from 8.5 to 7.0-7.5 (Test 3), and increasing orthophosphate from essentially zero to 1 mg/L  $\text{PO}_4^{3-}$  (Test 4). The frequency of



**Figure 2.3 Overview of single-metal (top) and galvanic-coupled (bottom) experiments performed at the ARTC testing facility for Project #3107 (Originally Figure 4.9 of Project #3107, which was originally published in Boyd et al., 2007)**

changes to the water chemistry allows measurement of the response of a pipe assembly to a change in water chemistry, although it may not indicate the longer-term behavior of the pipe assembly at that water chemistry. The frequent water chemistry changes also make it challenging to assess the long-term effects of galvanic connections. The baseline water

composition and the test conditions for experiments at the DC Water facility were different. Most importantly the water in all of the tests for all but one of the pipe loops contained approximately 3 mg/L as  $\text{PO}_4$  orthophosphate (the other still contained orthophosphate but at a lower concentration). The DC Water tests then examined the rate of change of disinfectant levels as well as changes in pH from the baseline level.

The pipe loops were frequently sampled for measurements of total lead and copper, other water quality measurements, and at the ARTC also for electrochemical measurements. Samples for lead and copper were collected from the recirculation line three times per week, and the water in the recirculating loops was changed weekly. The total lead accumulation in the reservoir over the course of each week was not measured. The pH and chlorine concentrations were monitored and adjusted daily to maintain fairly constant water chemistry. Local electrochemical potential profiles of pipes at the ARTC were generated weekly by measuring the open circuit potential for all of the electrode ports. The open circuit potential measures the equilibrium potential of the metal when there is not an electrical connection. The penny-sized coupons were periodically removed for analysis by scanning electron microscopy and X-ray absorption spectroscopy.

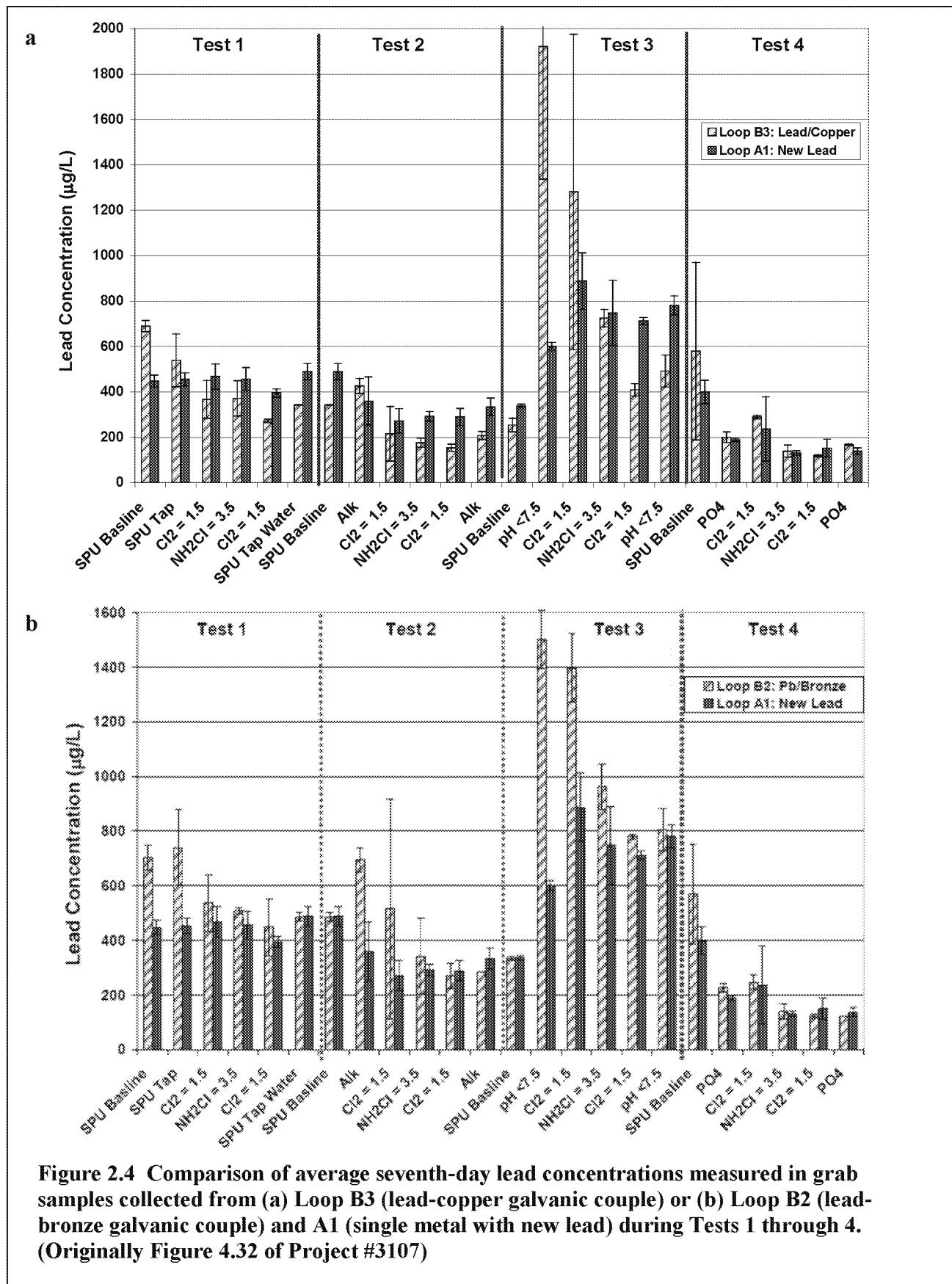
### ***Electrochemical Potential Profiles of Copper-Lead Connections***

To extend the measurements of the electrochemical potential profiles made for the pipes in the pipe loops, members of the project team conducted additional experiments with copper and lead coupons (sectioned 4-inch diameter pipe). The experiments investigated the influence of the mode of connecting the metals on the electrochemical potential profiles. One connection method was the same direct end-to-end configuration used in the pipe loop studies and the other was an external wired connection with the metal species in the water separated by an insulating spacer; the external connection is similar to that used in pipe experiments of the other project (Project #4088 (Chapter 11) and #4088b) being discussed in this review. The coupons were covered with tap water similar to that used with the pipe loops, and the open circuit potential was measured for the copper and lead surfaces as a function of distance along the coupon. In these experiments only electrochemical measurements were made and the water was not sampled for lead and copper.

### **Basis for Conclusions Regarding Galvanic Corrosion – #3107 (*Changing Disinfectants*)**

The report concluded that galvanic corrosion can cause periods of elevated lead release following changes in water chemistry but that these periods of elevated lead release are transient. The conclusions are reached through comparison of the results from a lead-only pipe loop with those from the dual-metal lead-copper and lead-bronze pipe loops (Figure 2.4). For the lead-copper pipe loop, the lead concentrations for Test 1 (baseline water) were about 50% higher for the dual-metal pipe loop than for the lead-only pipe loop for the first two weeks of the test and then only slightly higher for the next two weeks. The lead-bronze pipe loops also had higher lead concentrations than the lead-only pipe loop for the first four weeks of Test 1.

The largest differences in lead concentrations between the lead-only and lead-copper pipe loops were observed in Test 3 when the pH was lowered from 8.5 to less than 7.5. For the first two weeks after this pH change the water did not have any disinfectant and for the next two weeks free chlorine was added to a concentration of 1.5 mg/L  $\text{Cl}_2$ , a period during which the lead concentrations remained higher for the lead-copper pipe loop. For the remainder of Test 3 the



lead-copper pipe loop had either similar or lower lead concentrations to those of the lead-only pipe loop, including a two week period during which the pH was kept below 7.5 and again no disinfectant was present. During this return to the condition for which the largest difference in lead concentrations had been observed, the lead concentrations from the lead-copper pipe loop were actually lower than those from the lead-only pipe loop. The higher lead concentrations for the lead-copper pipe loop after the pH decrease were attributed to galvanic corrosion, and the subsequent disappearance of this difference was attributed to galvanic corrosion being a transient effect. The lead concentrations did decrease, although because their decrease occurred together with the addition of free chlorine, it cannot be determined whether the higher lead release for the lead-copper pipe loop would have persisted for longer in the absence of free chlorine. Similar observations of higher lead release during Test 3 were observed for the lead-bronze pipe loops, but the elevated lead concentrations persisted for at least six weeks. A change in alkalinity may also have induced lead release from galvanic corrosion for the lead-bronze pipe loops (Test 2), an effect that was not clearly apparent for the lead-copper pipe loops.

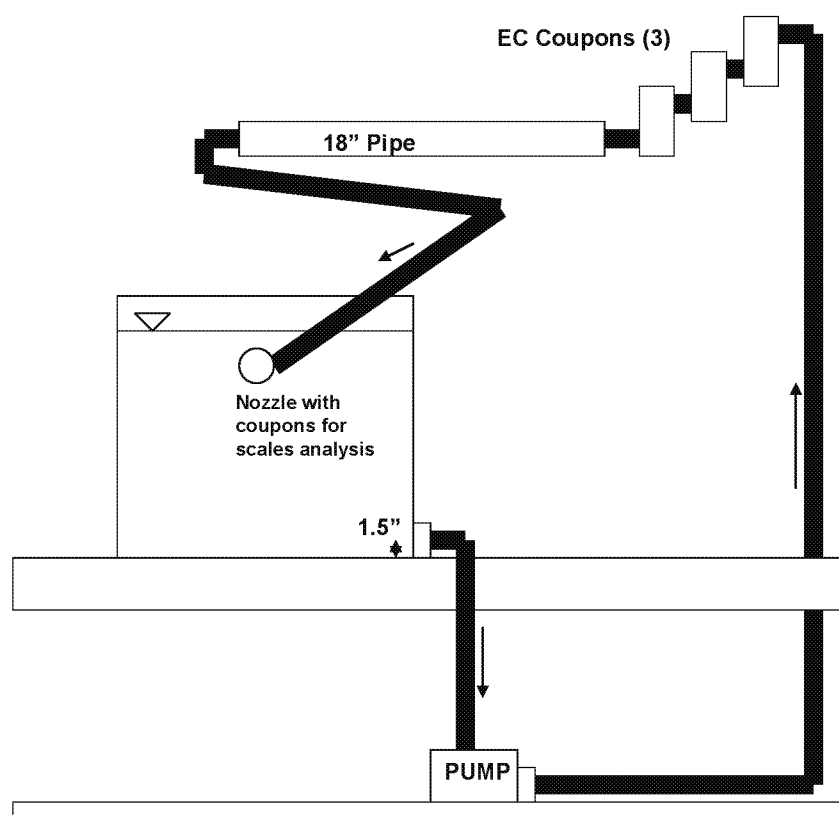
The experiments at the DC Water facility had lower lead concentrations than those in experiments at the ARTC. This may be attributed to the influence of the orthophosphate, which is often used as a corrosion inhibitor. Analysis of the lead coupons from the DC Water pipe loops indicated the presence of lead phosphate solids that have low solubility. With all lead concentrations being relatively low, the differences between lead-only and lead-copper or lead-bronze pipe assemblies were not as large. For the lead-bronze couple, the lead concentrations were often slightly higher than for the lead-only system. However, for the lead-copper couple the lead concentrations were actually slightly lower. Without having replicate experiments and having such small differences, it is not clear whether either of these differences were significant.

The measurements of the potential profiles of the electrically connected lead and copper coupons showed dramatic differences between the two methods of making the electrical connection. For connections made through direct end-to-end contact, the open circuit potential was only affected in the region very close (within about 1 inch) to the lead-copper joint. For the rest of the metal surfaces, the open circuit potentials were at values similar to those of lead or copper in the water by themselves. In contrast, for the lead and copper coupons connected through an external wire, the open circuit potential of the lead coupon increased by about 150 mV along its entire length. The open circuit potential of the copper coupon decreased by about 100 mV along its entire length.

### **Discussion of Experimental Approach and Conclusions Reached - #3107 (*Changing Disinfectants*)**

The project design worked to address the primary objective of determining the potential impacts of disinfectant changes on lead release for a variety of water chemistry conditions. The results also provided important insights regarding lead release associated with galvanic corrosion. Extension of the conclusions regarding galvanic corrosion to the potential for lead release during actual LSL replacements is limited by a few aspects of the experimental design. The most significant limitation was a method of sampling the water that did not account for all lead released from the pipes. Additional limitations include (a) the use of recirculating flow, (b) the lack of duplicate experiments, (c) the short durations over which water chemistry was held constant, (d) the use of pipes without well-developed pipe scales, and (e) the method of joining the lead and copper pipes.

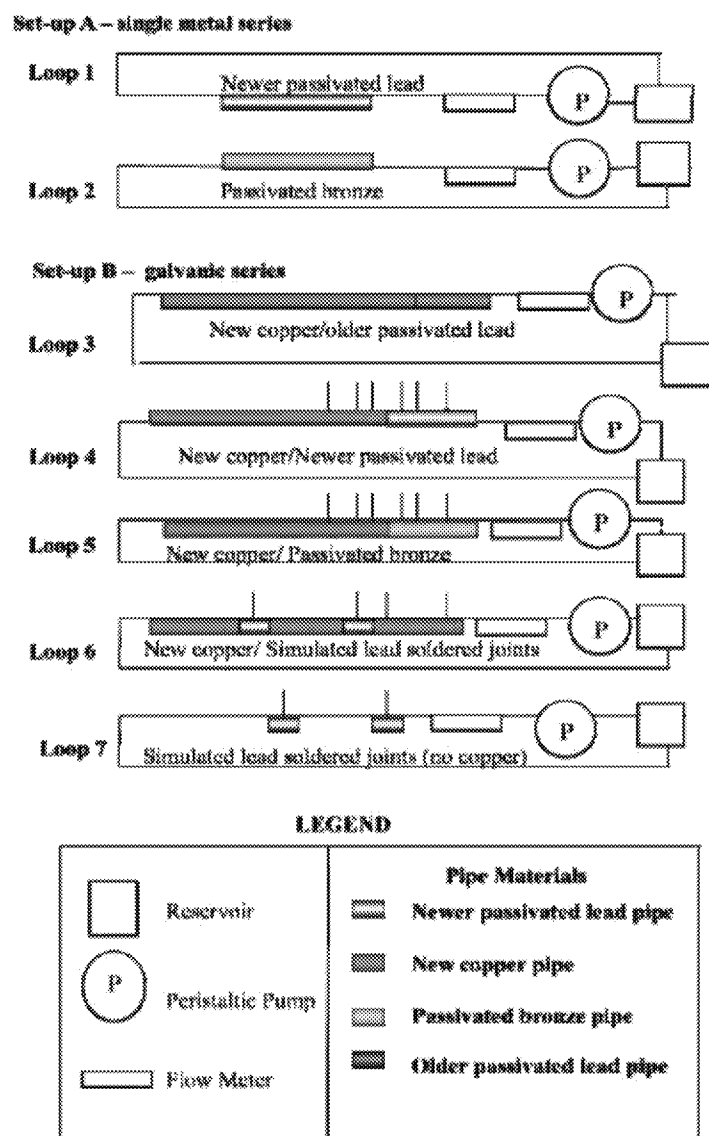




**Figure 2.5 Cross-sectional schematic of the recirculating pipe loop systems used in Project #3107. Samples were collected from the nozzle that returns flow to the 20-L reservoir (Originally Figure C.1 of Project #3107).**

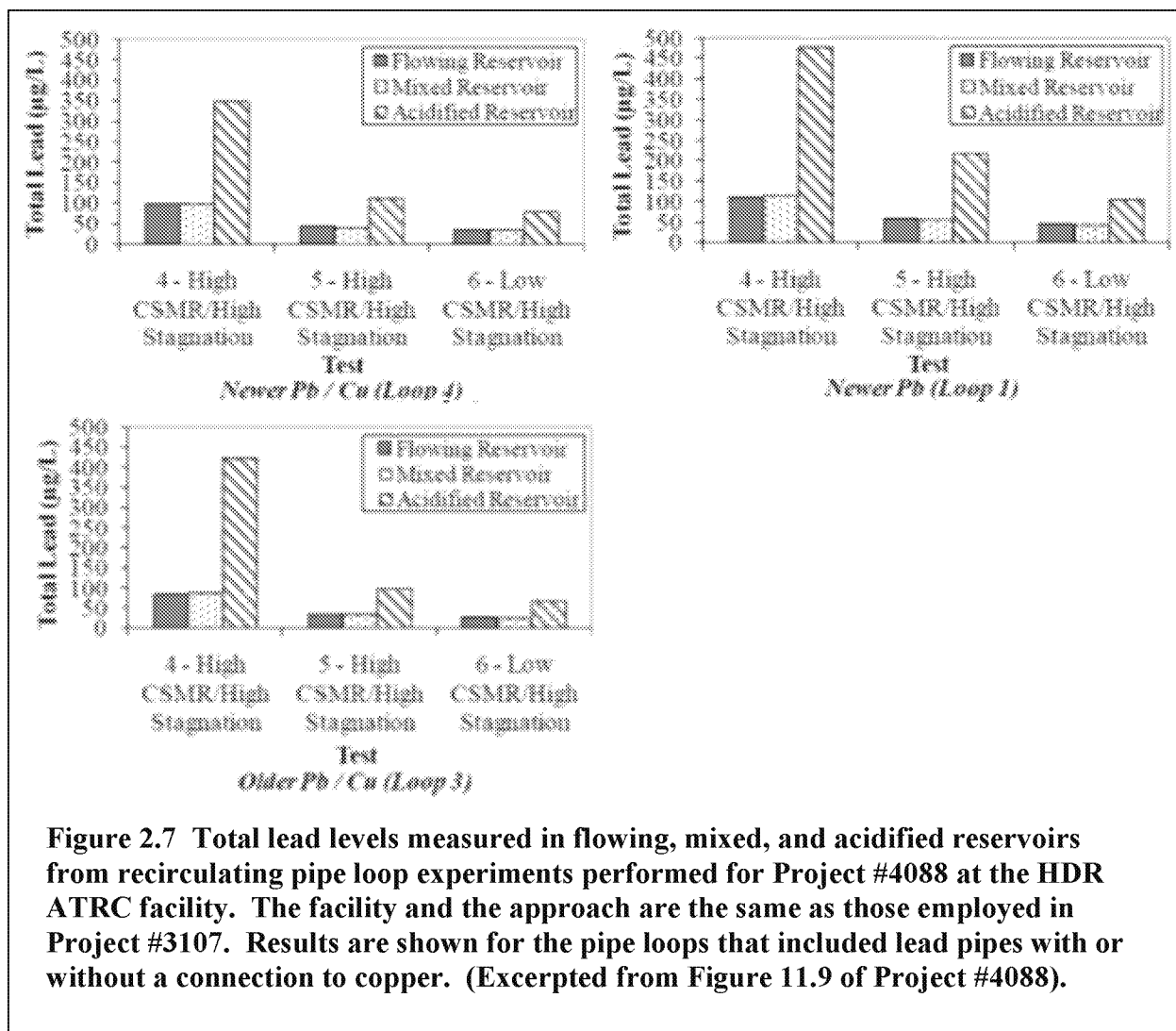
The reported lead and copper concentrations are those in grab samples collected from the recirculating line just before it enters the 20-L reservoir (Figure 2.5). This sampling approach does not account for any lead that could have accumulated in the reservoir. Such lead would include lead-containing particles that could settle out in the reservoir as well as lead adsorbed to the walls of the reservoir. Adsorption for the concentrations observed will likely be negligible, but accumulation of lead particles is a distinct possibility. The lead concentrations observed are high enough to result in the precipitation of lead-containing particles. Just as these particles were observed to form on the coupons for scale analysis, they may also form in the recirculating solution or become detached from the scales.

Measurements with the pipe loop system at the ARTC for both Projects #3107 and #4088 (Chapter 11) demonstrate that not all lead released from the pipes could be accounted for in a grab sample or even a sample from a well-mixed reservoir. The layout of the experiments for Chapter 11 of Project #4088 (Figure 2.6) was similar to that used for project #3107. For Project #4088 (Chapter 11), when a reservoir was acidified to 2% the lead concentration in the reservoir always increased (Figure 2.7). Samples from a well-mixed but unacidified reservoir were collected prior to reservoir acidification to allow this comparison. The increases were greatest (going from about 100  $\mu\text{g/L}$  to over 450  $\mu\text{g/L}$ ) for the first reservoir acidification, which was performed after a series of four tests over more than three months. However, even when



**Figure 2.6 Pipe loop setup used in Chapter 11 of Project #4088 (Originally Figure 11.1 of Project #4088)**

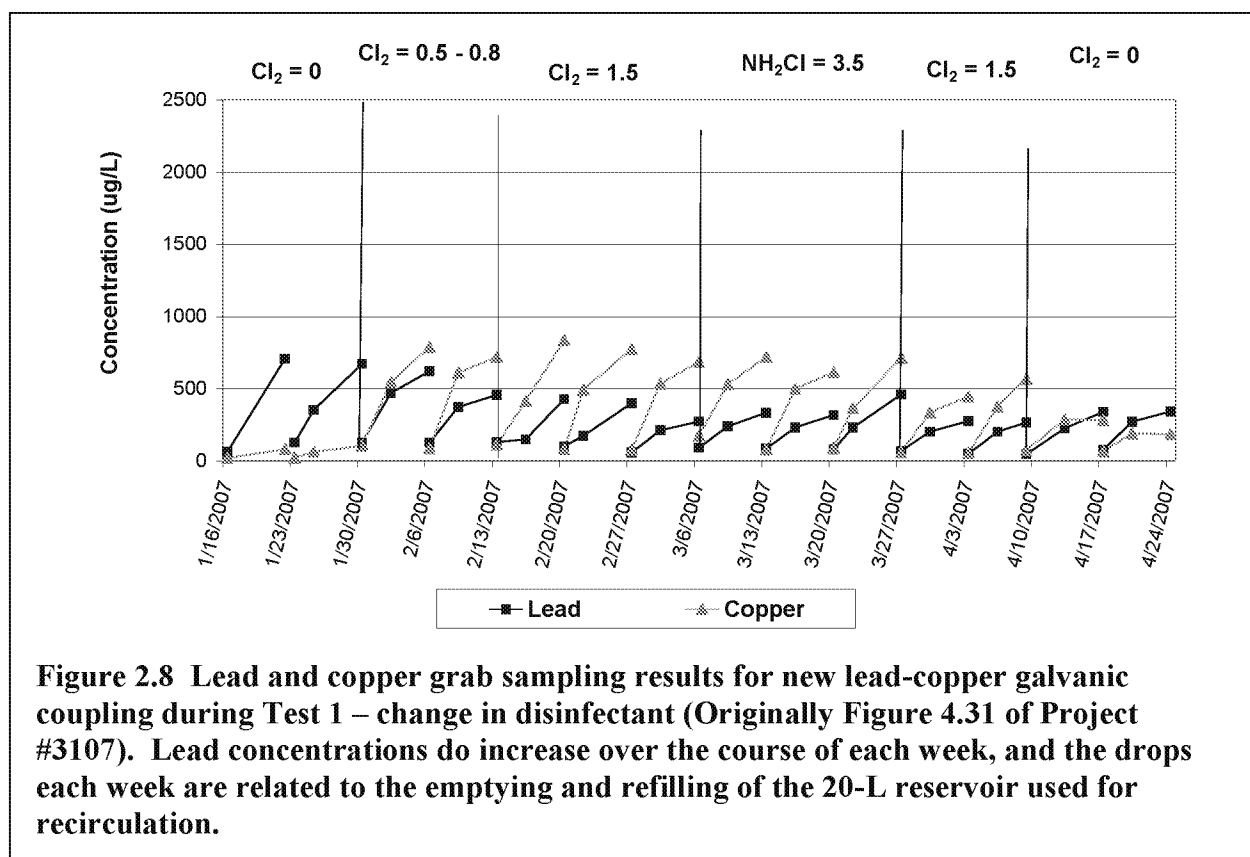
acidification was done after just 1-week tests, the reservoir lead concentrations still increased with the greatest relative increases of about a factor of four. Tests done as part of Project #3107 did not directly acidify the reservoirs after any tests. One test in which reservoir water with lead and copper from a previous test was circulated through tubing with the metal components bypassed showed that none of the lead in the water was removed by the reservoir or tubing during that recirculation; however, this test would not have been able to evaluate the presence of lead that had already deposited or sorbed to the reservoir materials. When the water in these reservoirs was acidified to 2% nitric acid after a period of more than two months in which some of the pipe assemblies were partially disassembled and no regular records were kept, the lead concentrations increased by more than a factor of ten (e.g. for the loop used for the new lead pipe from 149-181  $\mu\text{g/L}$  to 2639-3242  $\mu\text{g/L}$ ). Report #3107 (*Changing Disinfectants*) attributed the



**Figure 2.7** Total lead levels measured in flowing, mixed, and acidified reservoirs from recirculating pipe loop experiments performed for Project #4088 at the HDR ATRC facility. The facility and the approach are the same as those employed in Project #3107. Results are shown for the pipe loops that included lead pipes with or without a connection to copper. (Excerpted from Figure 11.9 of Project #4088).

increased lead upon acidification to the presence of lead-containing particles that were released during the handling of the pipes and other activities in the two months prior to acidification. This may indeed be the case, but unfortunately a more conclusive test of acidifying the reservoir immediately after a well-controlled and documented test was not performed for Project #3107. When such acidification was done after the test for Project #4088 (Chapter 11) the lead concentrations did increase, which would suggest that lead accumulation did occur in the tests of Project #3107 (*Changing Disinfectants*) using the same system and that this lead would not have been accounted for in a well-mixed but unacidified system. Subsequent experiments with recirculating flow using other systems have also observed significant lead accumulation in recirculation reservoirs that could only be measured following acidification (Arnold 2011; Giammar et al. 2011).

The impact of not accounting for lead that accumulated in the reservoirs in between the weekly changes of water on the overall conclusions is not clear. The reported lead concentrations from the grab samples almost certainly underestimate the amount of lead released from the pipes. The underestimation may be mild (a factor of two) or possibly quite significant (a factor of ten or more). The fact that the lead concentrations in the grab samples for a given



pipe loop did increase over the course of a week does suggest that the grab samples are responsive to changes in lead concentrations (Figure 2.8). Because the experiments were all performed in a consistent manner, the relative trends in the pipe loop grab samples may be representative of the trends in the overall lead release; however, this would require that the fraction of lead unaccounted for from pipe loop to pipe loop would be the same, and this assumption was not evaluated.

The use of pipe loops with recirculating flow has several important differences to the once-through flow that occurs in actual LSLs. Perhaps most important, the lead and copper concentrations can reach concentrations in a recirculating loop that will be much higher than those in a once-through flow system. These higher concentrations can accelerate the formation of corrosion products by reaching supersaturated conditions more quickly, and the formation of the corrosion products can serve to passivate the lead surface and inhibit further lead release. Indeed, the scale analysis of the penny-sized coupons has clear evidence for the formation of lead carbonate solids (cerussite and hydrocerussite) as well as some lead(IV) oxide minerals ( $\text{PbO}_2$ ) over the course of the experiments.

The daily adjustment of the concentration of chlorine disinfectant and the pH of the water in each recirculating loop was helpful in providing constant conditions over the course of the experiments, but such conditions are conservative with respect to observing lead release. For water stagnant in lead pipes, the chlorine can be depleted as it oxidizes the elemental lead of the pipe to lead(II) carbonates and the lead(II) carbonates to lead(IV) oxides. Further, localized lead release caused by galvanic corrosion can result in local regions of lower pH due to the Lewis acidity of the free lead ion ( $\text{Pb}^{2+}$ ). The impacts of this Lewis acidity on accelerated corrosion and inhibition of passivating scale development would be much greater for stagnant than flowing

conditions. In pipes with stagnant water the ratio of lead pipe surface area to water contacting the pipe is much lower than in the recirculating loops with 20 L of chlorinated water maintained at a stable pH being passed through the pipes.

The use of only single experiments for each dual-metal combination or single-metal condition is a limitation of the experimental design. The lead-copper and lead-bronze pipe loops partially serve as duplicates for galvanic corrosion effects, and the consistency of observations between them provides support for the significance of the trends, but duplicate (or more) experiments of each pipe-loop would have allowed an assessment of the statistical significance of the observed effects.

The experimental design was very ambitious, and while this allowed the evaluation of a large range of water chemistries it limited the definitive identification of any long-term effects. In particular, the increased lead release attributed to galvanic corrosion upon lowering the pH in the absence of a disinfectant was observed for two weeks, but then 1.5 mg/L  $\text{Cl}_2$  free chlorine was added. Whether the elevated lead release would have persisted in the absence of free chlorine, as may occur with water that has stagnated in a pipe, remains unknown. The changes in water chemistry may also influence the pipe surfaces in ways that affect the meaning of the tests done latest in the overall sequence. The pipe surfaces being tested in Test 2 are not the same as those being evaluated in Test 1 because Test 1 may have altered the pipe surface. This issue becomes further confounded in moving on to Test 3 (influenced by two previous tests) and Test 4 (three previous tests). Running the loops for a 2-week period with the original baseline water chemistry as part of all four tests did help to show that the lead concentrations were similar for the baseline composition that started each test, which suggests but does not prove that the pipe surfaces were comparable at the start of each test.

The use of a cleaned lead pipe instead of an aged lead pipe limits the relevance of the experimental conditions to actual lead release that would occur when connecting a copper pipe to an old lead pipe (e.g., as may occur during partial LSL replacement). Fresh lead pipes are known to corrode rapidly and their behavior is not representative of lead release from pipes upon which lead(II) and lead(IV) corrosion products have developed. The scale analyses do indicate the formation of corrosion products on new lead coupons over the course of the experiments, but the extent of scale development achieved in the experimental time period is likely to be considerably less than has occurred for pipes that have been in service for many decades.

The method of connecting the metal pipes for the pipe loop experiments is different from the method used in partial LSL replacements. Actual connections of lead and copper pipes are made with some form of coupling (often a brass coupling). Given this study's findings about the nature of the galvanic path on the open circuit potentials, the nature in which the pipes are connected could be important. In actual connections the couplings have stops against which the pipes abut that would prevent end-to-end contact. Brass is electrochemically similar to lead, and galvanic interactions between lead and brass can occur in addition to those between lead and copper.

## REVIEW OF CHAPTER 11 OF REPORT #4088

Project #4088 ("Impact of Chloride:Sulfate Mass Ratio (CSMR) on Lead Leaching in Potable Water"), primarily examined lead release from solder, including solder galvanically connected to copper, but Chapter 11 ("Utility H, WA (Pipe Loop Study)") included experiments using lead and copper pipes in the same recirculating pipe loop system used for Project #3107

(*Changing Disinfectants*) (Nguyen et al. 2010). While many of the observations and methods for the study of soldered connections and lead-copper connections are similar, the discussion below is focused on the experiments performed with pipes.

### **Summary of Experimental Approach – #4088 (Chapter 11)**

A set of pipe loop experiments were conducted at the same testing facility (the HDR Advanced Research and Technology Center) that conducted the experiments for Project #3107 (*Changing Disinfectants*). The experiments investigated the impact of CSMR on lead release from lead-containing materials, including lead and copper pipes that were electrically connected using an external wire approach that was also used in stagnant dump-and-fill experiments of Project #4088b (*Galvanic Corrosion*). The pipes studied included old lead pipe harvested from a utility that had not been cleaned as well as harvested lead pipe that had previously been reamed to expose fresh lead surfaces and then used in the 1-year experiments of Project #3107 (*Changing Disinfectants*). The pipes that had been reamed and then used are referred to as “newer passivated lead,” which reflects that potentially passivating corrosion scales may have developed in the previous year of experiments. For each pipe assembly type, only single experiments were performed (i.e., there were no replicates).

The water used in the experiments was local tap water in Redmond, WA, that was adjusted to pH 7.0-7.5 and received 3.5 mg/L as Cl<sub>2</sub> monochloramine disinfectant and 1 mg/L PO<sub>4</sub> orthophosphate. A series of tests were performed to examine lead release under different CSMR values (low of 1-2 and high of 8-10) and different flow-stagnation regimes. The pH and monochloramine were measured and adjusted 5-7 times per week, and the water in the recirculating reservoir was replaced with freshly prepared test water each week.

A range of sampling methods for measuring lead concentrations were used, and these were complemented by measurements of electrical current flowing through the wired connection of the lead pipes to the copper tubing. Lead concentrations were measured from (a) the pipe sections immediately following specified stagnation periods, (b) from the reservoirs while recirculation was ongoing, (c) from the reservoirs after they had been mixed, and (d) from the reservoirs after acidification of the water in the reservoir to 2% nitric acid and holding for 24 hours.

### **Observations Regarding Galvanic Corrosion – #4088 (Chapter 11)**

The pipe loop experiments led to clear conclusions that increasing CSMR increased lead release from galvanic corrosion, but no clear conclusions could be reached regarding the overall impact of galvanic connections on lead release due to different results for different sampling methods. When the water remaining in the reservoirs was acidified, the lead concentrations increased in all cases, often to concentrations that were 4-5 times those in the mixed but unacidified reservoir (Figure 2.7). These results suggest that lead had accumulated in the reservoirs during the recirculation phases of the experiments either by adsorption to the walls of the reservoirs (fluorinated polyethylene material) or by accumulation of solids that were not completely mixed prior to collecting the samples from the mixed reservoir. The mixed and recirculating reservoir samples were similar, which would be most consistent with lead deposition to the walls of the reservoir.

When considering the samples collected directly from the stagnant pipes, lead release was greater for lead pipe materials electrically connected to copper pipes than lead pipes alone. However, when looking at the lead concentrations in the acidified reservoirs, the total lead released was actually higher for the lead-only pipe assembly than for the lead-copper pipe assemblies. Given the complexity of the lead release in pipe loops with recirculation (i.e., the reservoir reflects lead released during multiple preceding periods of stagnation and of recirculating flow), the samples collected following stagnation may be the more reliable indicator of lead release, especially particulate lead, caused by galvanic corrosion. The tests for which data are reported each lasted only one week (1 week at high CSMR and 1 week at low CSMR) so no conclusions regarding the duration of galvanic corrosion effects could be made.

Galvanic current measurements and the impact of CSMR provided evidence for galvanic corrosion. Measurable galvanic currents were present for the lead-copper pipe assemblies that were electrically connected through the external wire, and currents were consistently higher at the high CSMR value. Galvanic current densities of up to  $0.23 \mu\text{A}/\text{cm}^2$  were measured for lead-copper assemblies at high CSMR, which correspond to a current of  $46 \mu\text{A}$ . This value is lower than but still on the same order of magnitude as the current of  $60\text{--}70 \mu\text{A}$  measured for a 12-inch lead pipe section connected to copper in dump-and-fill experiments using water with a high CSMR value as part of Project #4088b (*Galvanic Corrosion*). The pipe loop studies also resulted in higher lead concentrations at higher CSMR values for the lead-copper pipe assemblies. The measured lead concentrations were much lower than those that would have resulted from galvanic corrosion if all of the oxidation of the lead pipe resulted in lead release; this is consistent with the process of galvanic corrosion oxidizing the  $\text{Pb}(0)$  of the lead pipe to  $\text{Pb}(\text{II})$  that may either be present as a solid corrosion product in the pipe scale or be released to the water. The presence of orthophosphate might have promoted the precipitation of low solubility lead(II) phosphate solids that were retained in the pipe scales.

### Discussion of Experimental Approach – #4088 (Chapter 11)

The pipe loop experiments provided data of only limited value because of differing results depending on the method of lead sampling. Water collected from pipe sections after stagnation had higher lead concentrations for pipes that experienced galvanic corrosion, but acidified reservoir samples were actually higher for the lead pipe alone. The accumulation of lead in the reservoir is a serious issue that should be accounted for in interpreting the results of recirculating pipe loop studies. The loss of lead can attributed to adsorption to the reservoirs or settling of particulate

The divergent results from the pipe loop experiments depending on sampling method also point to the problem of not including replicate experiments. All conclusions are based on a single lead-only pipe loop and two lead-copper pipe loops that used different configurations of the lead pipe materials. Replicate experiments would be essential to understanding whether the conflicting conclusions are the result of some physical or chemical phenomenon or just the result of uncertainty in the behavior of individual pipe sections.

The results suggest that the nature of the pipe scale can have a dramatic impact on lead release. Interestingly, lead release for the lead-copper pipe assemblies was actually higher when using old lead pipe than the newer lead pipe. The report suggested that the differences may be due to the 1-year of experiments with the newer lead pipe having generated a more stable pipe scale than was present on the older lead pipe. The nature of the pipe scale, and not just its age,

impacts the release of lead, especially particulate lead. The year of previous experiments with the newer lead pipe, which had nearly continuous recirculation, would also have prevented the buildup of any corrosion scales that might be easily mobilized by changes in flow; the older lead pipe may have had corrosion scales susceptible to such release. Reconditioning older pipes to recirculating flow after harvesting the pipes could minimize such an effect, but it is not clear that any reconditioning of the older lead pipe was performed.

## **REVIEW OF REPORT #4088B (*GALVANIC CORROSION*) SECTIONS RELATED TO GALVANIC CORROSION AND ASSOCIATED WORK**

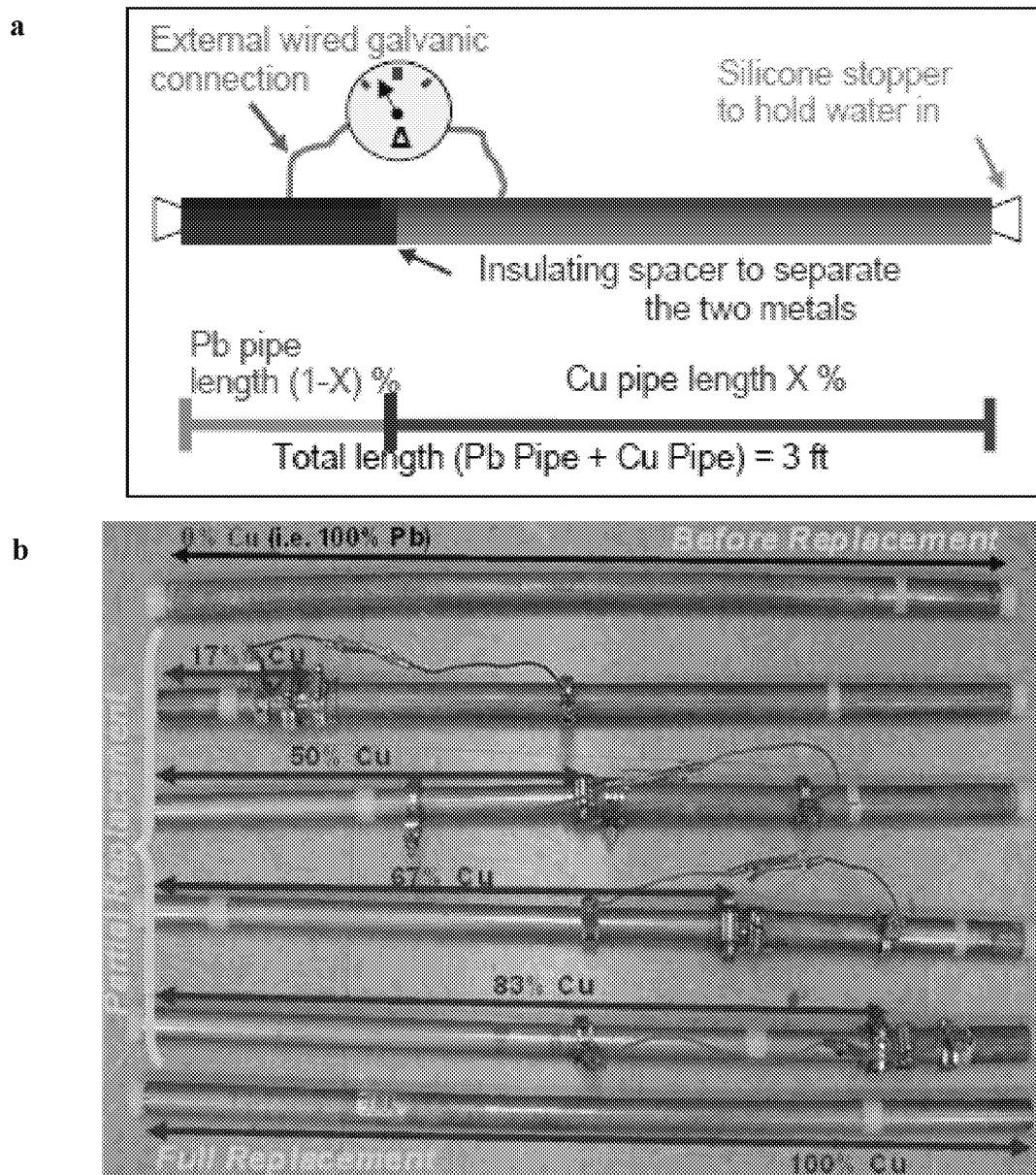
Project #4088b (“Contribution of Galvanic Corrosion to Lead in Water after Partial Lead Service Line Replacements”) used electrically connected lead and copper pipes to investigate the duration of lead release associated with galvanic corrosion and to assess the effects of the chloride-to-sulfate mass ratio on lead release. Experiments were conducted using test rigs with a static dump-and-fill approach to examine lead release to water after periods of stagnation, conditions which were selected to represent a “worst case” scenario for lead release.

### **Summary of Experimental Approach – #4088b (*Galvanic Corrosion*)**

Three sets of pipe rigs were prepared with different relative lengths of copper and lead pipes (for a total of 3 ft in each assembly) being studied in each of the sets (Figure 2.9). For each set a pure 3-ft section of lead pipe and a pure 3-ft section of copper pipe were used for reference, and four different length ratios (17% Cu, 50% Cu, 67% Cu, and 83% Cu) of copper to lead pipe were investigated to assess impacts of galvanic corrosion. An insulating spacer was included between the lead and copper pipes, and the electrical connection to provide the possibility of galvanic corrosion was made through an external wire that was connected to grounding straps on each of the pipes. The strap on the lead pipe section was placed at approximately the midpoint of the lead pipe. Each of the three sets used a different lead pipe. One set used new lead pipe and the other sets used pipes that had been used in previous experiments. These used pipes are referred to as “Old Pb pipe A” and “Old Pb pipe B”, although they are “old” only relative to the newly purchased lead pipe and not relative to the time periods of harvested lead pipes from distribution systems. The “old” lead pipes in the study were new pipes that had previously been used in experiments of 4-12 months. Further, the “old” lead pipes were treated with a pH 2.0 solution of sulfuric acid prior to their use in experiments. This treatment probably removed a considerable amount of the pipe scale, although visual evidence does indicate that some scale did remain on these pipes.

The pipe assemblies were filled with synthetic tap water and allowed to stagnate for unspecified lengths of time. The water chemistry of the synthetic tap water was modified at various times in the experiment. The pipes were filled and emptied three times per week, and a composite sample from each of the three emptying phases was used for weekly analysis of total lead. In addition to measuring the total lead, the current passing through the wire that connected the lead and copper pipes (i.e., the galvanic current) was periodically measured. In one of the sets of pipe assemblies the galvanic current was measured at different distances along the lead pipe by joining multiple 0.5-ft lead pipe sections with electrical connections between each (Figure 2.10). The pipe assemblies were first used with synthetic tap water with a low chloride-to-sulfate mass ratio (CSMR) of 0.2 for 11 weeks, and the synthetic tap water then had its CSMR





**Figure 2.9 Research approach ((a) schematic and (b) photograph) followed in Project #4088b for connecting copper tubing and lead pipes. (Originally Figures 2 and 3 of Project #4088b).**

increased to 16 while holding all other values constant for 14 weeks. After the 14 weeks of high CSMR with the galvanic connection in place, the electrical connection was disconnected and the experiments were performed for an additional six weeks with the same high CSMR water. In a final phase of the experiments, the wires were reconnected and the alkalinity of the high CSMR water was increased from 15 mg/L  $\text{CaCO}_3$  first to 50 mg/L  $\text{CaCO}_3$  for four weeks and then to 100 mg/L  $\text{CaCO}_3$  for an additional ten weeks.



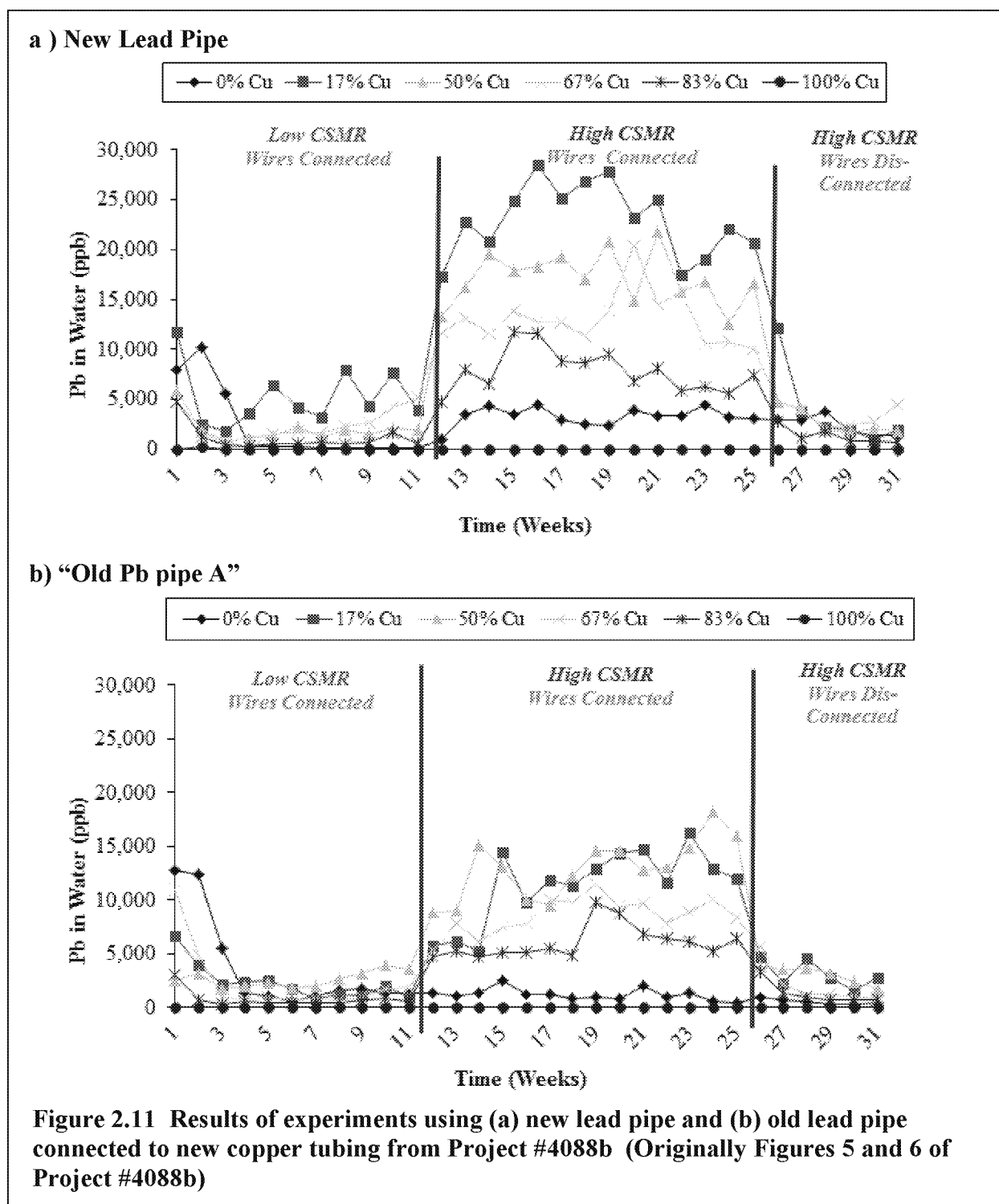
**Figure 2.10 Experimental system using one of the lead pipes (Old lead pipe B) to examine galvanic current measurements as a function of distance from the junction with copper (Originally Figure 14 of Project #4088b)**

### **Basis for Conclusions Regarding Galvanic Corrosion – #4088b (*Galvanic Corrosion*)**

The report on the static lead-copper pipe rigs concluded that galvanic corrosion increased lead corrosion for periods of at least 25 weeks and were not decreasing with time. The impact of galvanic corrosion on lead increase was exacerbated by an increase in CSMR, and intriguingly it was not alleviated by increasing the alkalinity. These conclusions were reached by comparing lead release from the electrically connected copper and lead pipe rigs with lead release from both the pure lead pipe and from the copper and lead pipe rigs without the electrical connection (Figure 2.11). The galvanic current increased with CSMR and did not decrease with addition of alkalinity.

The lead concentrations were clearly higher for the lead-copper pipes with galvanic connections than for the pure lead pipes. This effect was apparent for all three configurations of lead pipe studied; the pure section of lead pipe was sometimes higher during the initial weeks of the experiment, but after values stabilized for a given water composition it was always lower than for the lead-copper pipe rigs. Illustrating the significance of the effect, the lead concentrations from a 3-ft length of lead-copper assembly that had only 0.5 ft of lead were higher than those from a 3-ft length of pure lead pipe. The impact of the electrical connection was even more pronounced when the CSMR value of the water was increased from 0.2 to 16. The lead concentrations dropped quickly when the electrical connection between the lead and copper pipes was broken.

The impact of the CSMR on galvanic corrosion has been hypothesized to be caused by the precipitation of a lead sulfate solid at the site of lead release that does not occur at high CSMR (i.e., low sulfate relative to chloride) and that is worsened by the formation of soluble lead chloride complexes (Nguyen, Stone, and Edwards 2011). The corrosion products at the joints have not been identified, so the hypothesis cannot be confirmed by identification of lead sulfate, which is a relatively soluble solid as compared to other lead-containing solids. Lead sulfate has rarely been observed in previous investigations of corrosion products on lead pipes, although it was observed as a corrosion product on lead pipe joined to copper pipe through a wiped joint (DeSantis, Welch, and Schock 2009). The formation of lead sulfate and a role for it in limiting further lead release would be unique to the low pH and high lead concentration (10's of mg/L) environment that may develop at sites of highest galvanic corrosion. Localized regions of low pH are generated at the areas on the lead pipe where lead release is greatest due to the Lewis acidity of  $Pb^{2+}$ ; measurements of pH at the surface of leaded solder galvanically connected to copper dropped as low as pH 2.5 (Nguyen et al. 2010). Interestingly, the increase in the



alkalinity to values as high as 100 mg/L  $\text{CaCO}_3$  did not affect the lead release. Separate electrochemical experiments with wires made of lead to which a potential was applied using a potentiostat confirmed the observed effect of sulfate on both lead release and measured current; however, this study did observe a benefit of increasing alkalinity above 10 mg/L  $\text{CaCO}_3$  (Nguyen et al. 2011).

Galvanic current measurements indicated that galvanic corrosion was localized in the lead pipe sections closest to the copper pipe for the system with the configuration shown in Figure 2.10. For a pipe with current measured every 0.5 ft along the lead pipe, 95% of the current was associated with the 0.5 ft section closest to the junction with the copper. The galvanic current did increase with the percentage of the 3-ft length of pipe that was lead for almost all of the pipe types and waters studied. Although the lead release was not always highest for the same pipe that had the highest galvanic current, these results could be explained by considering that not all of the oxidation of lead that is measured by galvanic current will result in lead release; oxidized lead can also result in the conversion of Pb(0) to Pb(II)-containing solids that remain as part of the corrosion scale.

### **Discussion of Experimental Approach and Conclusions Reached – #4088b (*Galvanic Corrosion*)**

The project results clearly showed the impact of the electrical connection and the CSMR on lead release for the types of lead pipes studied and the nature of the electrical connection studied. As directly described in the report, the experimental approach may be considered a “worst case” scenario for lead release, particularly with respect to the long stagnation times and low volumes of water that contacted the pipes over the duration of the experiments. There are some obstacles to estimating the impacts of actual LSL replacements from the experimental results. Indeed, the report’s conclusions note that more research would be needed to examine lead release under more realistic flow regimes, with actual brass couplings used in practice, and with aged and not new lead pipes. In addition to these issues, a few other aspects of the experimental design are discussed below.

The long stagnation times from only emptying and filling the pipes three times each week represent worst case scenarios for both lead release in a particular cycle and for the development of any passivating corrosion scales. Long stagnation times allow lead release into the same volume of water to achieve high concentrations. With long stagnation the alkalinity that may buffer pH decreases caused by galvanic corrosion can be consumed completely near the pipe surface, and as the pH drops lead release can increase further. The chlorine species that can help accelerate the oxidation of the lead metal of the pipe to Pb(II) species will be consumed during stagnation, and only limited scale development will occur with each filling cycle; when free chlorine is used, this process can be accelerated further and may also result in Pb(IV) solids, but monochloramine was used in this study. With three weekly emptying and filling cycles, each pipe comes in contact with only 0.78 L of water each week, and this water only has the composition of the synthetic tap water immediately after filling. Pipe scales will develop on these pipes much more slowly than they would on pipes that receive continuous or intermittent flow of water with the target pH, alkalinity, and disinfectant.

The use of new lead pipes, which inherently do not have any corrosion scales, further represents a worst case scenario. For actual LSL replacements, the lead pipes that are connected to copper pipes will have had corrosion scales develop over many decades. Even the old lead pipes used in the experiments had been used for only one year or less and these had corrosion scale partially removed in the sulfuric acid washing step. The use of new lead pipes and cleaned pipes in experiments has the advantage of using materials that are initially more reproducible and can result in less random variation from pipe to pipe, which is helpful when assessing the significance of differences caused by different electrical connections or water chemistries. The

use of new pipes also eliminates the potential for lead release from the disturbance of pre-existing pipe scales.

Electrically connecting the lead and copper pipes through an external wire allows for direct measurements of galvanic current, but it is not representative of the nature of the connections between lead and copper pipes in practice. In current partial LSL replacements a portion of new copper pipe will be connected to the remaining section of old lead pipe through a coupling. Most of the couplings that are used are brass, a conductive metal that would allow electron flow from the end of the copper pipe to the end of the lead pipe. If electrical connections made through external wires do not result in similar corrosion behavior to those made with couplings, then the results of the study will not be directly relevant to partial LSL replacements.

The results of the project could have been interpreted further if some measurements of dissolved lead were made in addition to those of total lead. Total lead concentrations of nearly 30,000 µg/L were achieved in some experiments. This is well in excess of the solubility of most lead-containing solids, so it is likely that most of this lead is present as particulate. Information on dissolved lead concentrations may help in assessing the hypothesis regarding lead sulfate precipitation as hindering lead release at high sulfate concentrations. Subsequent measurements reported in an article based on this study confirmed that particulate lead was dominant (Triantafyllidou and Edwards 2011). Measurements of the pH of the water after the stagnation periods would also have been helpful in assessing the degree to which long stagnation times led to high lead concentrations.

## **COMPARATIVE ASSESSMENTS OF PROJECTS #3107, #4088 (CHAPTER 11), AND #4088B AND NEEDS FOR FUTURE RESEARCH**

The projects had different research objectives and accordingly they followed different research approaches. The different conclusions reached by Projects #3107 and #4088b can be related to the different experimental methods. Both projects generated valuable datasets that provide information on the potential for lead release in response to changes in water chemistry, and both also yielded important insights into impacts of galvanic corrosion on lead release. Project #3107 determined that impacts of switching disinfectant from free chlorine to chloramines were minimal for pipe materials that had not accumulated PbO<sub>2</sub>. Project #4088b (*Galvanic Corrosion*) identified the importance of the chloride-to-sulfate mass ratio on lead release from lead-containing materials that were electrically connected to copper. Both projects confirmed that lead release associated with galvanic corrosion is dominated by the section of lead pipe nearest to the junction with the copper pipe. As with almost any research project, in hindsight it can be seen that both projects had some aspects that limit the extent to which their results can be generalized, in this case to predict the role of galvanic corrosion in lead release following partial LSL replacements.

### **Potential Reasons for Reaching Different Conclusions Regarding Galvanic Corrosion**

Projects #3107 and #4088b observed different impacts of galvanic corrosion on lead release because of significant differences in their research approaches. The most significant differences were in (a) the flow/stagnation regimes used, (b) the starting lead pipe materials, (c) the water chemistry, and (d) the method of making electrical connections between copper and

lead pipes. The first three factors are interrelated and are the most likely explanations for the different results from the different projects. While some interesting observations were made regarding the nature of the electrical connections, for all projects discussed thus far, galvanic corrosion appears to be localized on the region closest to the copper pipes and the differences in the method of connection may not explain the different results.

### ***Different Stagnation and Flow Regimes***

The dump-and-fill approach of Project #4088b (*Galvanic Corrosion*) with long stagnation times was used to represent a worst case scenario for lead release due to galvanic corrosion. In contrast, in several respects continuously recirculating flow with frequent adjustment of pH and chlorine levels may be considered a best case scenario for lead release. The long stagnation times in the dump-and-fill approach provide long times for lead concentrations to reach high values. In the recirculating flow experiments, the lead released over long periods of recirculation is diluted throughout the entire volume of recirculating water (initially 20 L). The stagnation allows for high lead concentrations to be reached in local regions of particularly high galvanic corrosion, and the Lewis acidity of the  $\text{Pb}^{2+}$  ion can drive a feedback mechanism in which the pH in the local region decreases and drives further galvanic corrosion. Such a mechanism cannot occur in the recirculating loops because the water in the loop is continuously recirculated, which provides mixing and prevents the development of any local low pH zones on the pipe surface. Further, the frequent adjustment of the pH of the recirculating water helps prevent any decreases in pH anywhere in the system.

The dump-and-fill approach also represents a worst case for the development of pipe scales that may eventually passivate the lead pipe surface against large lead release during galvanic corrosion. Not only do the low pH values reached during locally high lead release limit development of corrosion products, the dissolved constituents that might help promote scale development (e.g., chlorine disinfectants, dissolved oxygen, and alkalinity) can be consumed during each stagnation period. Further, the development of scale products is limited by the rate of supply of freshly prepared water. In the dump-and-fill approach, the pipes only receive 0.78 L of water each week and the water composition changes over time. In contrast, the pipes in the recirculating pipe loop system were contacted with 20 L of freshly prepared water each week. This is not only 25 times more water to aid in scale development, this water is also maintained at chlorine disinfectant and pH values that can promote scale development.

The lead concentrations (up to about 500  $\mu\text{g/L}$ ) in the acidified reservoirs of the pipe loop rigs for Project #4088 (Chapter 11) were orders of magnitude lower than those in the dump-and-fill experiments of Project #4088b (*Galvanic Corrosion*), and the lead concentrations achieved during 8-h stagnation in the pipe loop rigs were also much lower than those achieved for longer stagnation times in the dump-and-fill rigs. While concentrations are not reported, lead release of 0.22  $\mu\text{g/cm}^2$  was reported for the newer lead pipe connected to copper pipe for 8-h stagnation with a high CSMR value for Project #4088 (Chapter 11); this corresponds to a total lead concentration of 127  $\mu\text{g/L}$ . In contrast, the dump-and-fill experiments at high CSMR values had concentrations on the order of 15,000  $\mu\text{g/L}$  for a high CSMR water and a 12-inch lead pipe section connected to copper (i.e. the 67% copper rig with a 3-ft length). These differences may not be surprising given the (a) greater time for passivating scale development, (b) presence of orthophosphate corrosion inhibitor, and (c) shorter stagnation time for the experiments in the pipe loop apparatus.

The recirculating pipe loops can promote corrosion scale development orders of magnitude faster than in the dump-and-fill apparatus, and this difference can explain the different conclusions reached regarding whether or not elevated lead release from galvanic corrosion is a transient effect. Neither approach was designed to directly represent real LSL connections. If followed in an actual water connection, the dump-and-fill approach would provide on the order of 0.78 L of water per week, which is orders of magnitude lower than typical use rates. It therefore does represent a worst case for scale development that might limit lead release. In contrast, with respect to providing water of a fixed composition that can help develop passivating scales, the continuously recirculating flow of 0.5 gpm would correspond to a connection that used 5040 gallons per week, a value that is on the high end of typical household use and without any stagnation events. Neither approach was designed to have a flow regime representative of that for actual connections as that was not an objective of either study. However, as noted in the conclusions of both reports, they should be read cautiously with respect to applying their results to what may occur in actual partial LSL replacements.

Evaluating lead release after periods of stagnation is critical to estimating impacts on tap water lead levels since stagnation periods both represent the times when lead concentrations will be highest and are prescribed prior to sampling in accord with the Lead and Copper Rule. The pipe loop experiments performed at the ARTC facility for Project #4088 (Chapter 11) have the most representative flow conditions for actual service connections in providing periods of recirculating flow that promote scale development while also examining lead release after periods of stagnation. Unfortunately, the interpretation of these experimental results was challenged by the lack of replicate experiments and by different sampling methods that yielded different results. Most significantly the total lead released from the pipe assemblies was underestimated by grab samples or unacidified samples from well-mixed reservoirs, an issue already discussed. Because of these limitations no conclusions about lead release were drawn from this set of experiments.

### ***Different Lead Pipe Materials***

The differences in flow regime just discussed impact the development of pipe scales of corrosion products that may limit subsequent lead release to solution. The two projects also used pipes that had different levels of scale development at the start of experiments. Given the potential importance of scale development in passivating pipes, no direct comparison of results of studies that used different pipes can be made. Project #4088b (*Galvanic Corrosion*) used new lead pipes and nearly-new acid-cleaned lead pipes that would have either no scale or limited scale initially present. In a completely separate study, a dump-and-fill approach took nine weeks of emptying and filling the pipes five times per week to see a large decrease in lead concentration that likely corresponded to appreciable scale development (Xie and Giammar 2011); the dump-and-fill experiments of Project #4088b were refilled three times per week. In contrast Project #3107 started with lead pipes that had been reamed to expose new lead surfaces, but these could have passivated more quickly due to the recirculation of water of fixed composition that was just discussed.

The presence of pipe scales of corrosion products may not only impede corrosion it can also alter the fate of lead that is oxidized during corrosion. When corrosion products are not present in a pipe scale, oxidation of the Pb(0) of the lead pipe will result primarily in the release of lead to solution. In contrast, when pipe scales are present, the Pb(II) produced by corrosion

can be released to solution or be retained in the scale of corrosion products. The observations in the pipe loop study of Project #4088 (Chapter 11) of currents that suggested that much more Pb(0) was being oxidized than was being released to solution are consistent with this limitation of release of oxidized lead following corrosion of the underlying lead pipe. Such discussion of not all oxidized lead being released to solution was also included in the comparison of measurements of currents and lead concentrations from the dump-and-fill experiments of Project #4088b.

With one exception all of the experiments in both projects with lead and copper pipes that are galvanically connected did not use aged lead pipes. In practice, partial LSL replacements will connect aged lead pipes that will contain pipe scales of corrosion products to new copper tubing, although a small freshly cut lead surface is created at the time of making the replacement. Only one experiment in the Project #4088 (Chapter 11) pipe loops used an aged lead pipe connected to a copper pipe, but given the problems already discussed for that experiment, no conclusions regarding lead release for aged lead pipes can be made. However, a comparison of the results of Projects #3107 and #4088b does suggest that the development of pipe scales can decrease lead release to solution even if they have only a small impact on the electron flow involved in galvanic corrosion.

### ***Different Water Chemistry***

The previous projects evaluated lead release to waters with different water chemistry, and such differences could certainly impact lead release as well as the development of pipe scales. Both reports acknowledge in their conclusions that different results from those observed in the specific study may be found for different water chemistry. Project #3107 (*Changing Disinfectants*) explored a large range of water compositions, and the water chemistry was maintained at target values by periodic adjustment throughout the recirculating flow experiments. Lead release was consistently greater for lower pH. Project #3107 found the largest galvanic corrosion-associated lead releases upon a deliberate decrease in pH, and Project #4088b (*Galvanic Corrosion*) attributed high lead releases to local regions of low pH on the lead pipe surface. For Project #3107 the addition of orthophosphate resulted in the lowest lead concentrations of the four test phases and the tests at the DC Water facility, which all included orthophosphate, had lower lead concentrations. However, while orthophosphate may have benefits in some cases for systems with connections that allow galvanic corrosion, in other cases orthophosphate addition actually increased lead release or had no effect (Arnold 2011).

### ***Different Methods of Electrically Connecting Lead and Copper Pipes***

Project #3107 (*Galvanic Corrosion*) joined lead and copper pipes through a direct end-to-end connection, and Projects #4088 (Chapter 11) and #4088b (*Galvanic Corrosion*) provided an external wired connection of the lead and copper pipes that could be either left connected or could be disconnected. Through different approaches both Project #3107 and #4088b suggest that galvanic corrosion processes are localized on the portion of the lead pipe that is closest to the junction with the copper pipe. Project #4088b (*Galvanic Corrosion*) measured galvanic corrosion in consecutive 0.5-ft sections and found that 95% of the current is carried by the section closest to the copper pipe.



The follow-up work by the research group that performed Project #3107 (*Galvanic Corrosion*) found that the profiles of the open circuit potentials along the length of a lead metal section connected to a copper section were different for the direct end-to-end and the externally wired methods of making the connections. For the direct end-to-end connection, as in the pipe loop experiments, the open circuit potential was only altered for the region closest to the junction. For the externally wired connection the potential was altered over the entire length of the lead section. The open circuit potential provides a measure of the electrochemical driving force between two electrodes that are not electrically-connected (i.e. an open circuit), but since this is not the situation for an electrically conductive connection made between lead and copper its relevance to lead release is not clear. The open circuit potential measurements are different than the current measurements made in Projects #4088 (Chapter 11) and #4088b (*Galvanic Corrosion*) for which the circuit was closed. Unfortunately, the study in which the intriguing measurements of open circuit potential measurements were made for the two connection approaches did not include measurements of galvanic current or lead concentrations. While the open circuit potentials are different, it remains to be determined whether the lead releases would be different. In Project #4088b (*Galvanic Corrosion*) the current was still localized nearest the junction. Because the current is the property most directly related to the rate of corrosion of the lead pipe, the corrosion may still be localized near the junction with the copper pipe for the externally wired connection even though the open circuit potentials were altered over larger sections of the pipe.

The available results from the projects also do not provide a clear picture of the impacts of the localized nature of galvanic corrosion on overall lead release. Measurements of lead concentrations at discrete positions along the length of the lead pipe would have nicely complemented the measurements of either galvanic current or open circuit potential. The results of Project #4088b (*Galvanic Corrosion*) in which different lengths of lead pipe were externally connected to copper pipes could potentially examine the relative contributions of lead from the zone nearest the copper pipe and the remainder of the pipe. If the lead release is dominated by galvanic corrosion in the 0.5-ft section closest to the lead pipe, then the lead concentrations and the galvanic currents should be expected to be very similar for each of the lead-copper assemblies. Unfortunately, the lead concentration results do not have any consistent trends in this regard. For some pipes and conditions (high CSMR and new lead pipe), the lead concentration increases with increasing amounts of lead, which would suggest that galvanic corrosion may be influenced over the full length of the lead pipe available; however, for other pipes and conditions (low CSMR and new lead pipe, high or low CSMR with old lead pipe) the lead concentration does not have a clear correlation with lead pipe length, which would indicate that lead release is dominated by galvanic corrosion over a short fixed length of pipe that is the same regardless of the overall lead pipe length. The galvanic current measurements suggest that galvanic corrosion is limited by the region closest to the copper pipe. Although the galvanic current does increase with increasing amounts of lead pipe, the increase is far less than what would be proportional to the lead pipe length; when increasing the lead pipe length from 0.5 ft to 2.5 ft (a five-fold increase), the current only increases from about 60  $\mu\text{A}$  to about 85  $\mu\text{A}$  (an increase of less than 50%). While the synthesis of all of the results suggest that galvanic corrosion is limited to the region closest to the copper pipes in both sets of experiments and cannot explain the differences in the lead releases observed in the two studies, the differences in open circuit potential remain intriguing and merit further study in combination with other measurements.

### Need for Additional Research on Galvanic Corrosion Following Partial LSL Replacement

The differences in the conclusions reached in Projects #3107 and #4088b highlight the need for additional research on the impacts of galvanic corrosion on lead release following partial LSL replacement. Many of the recommendation outlined below were included in the reports to the projects just discussed.

- **To assess impacts on partial LSL replacement, relevant pipes and connection methods should be used.** Actual LSL replacements will connect aged lead pipes to new copper pipes with some form of pipe coupling (often a conductive brass coupling). While there are challenges to working with harvested lead pipes (e.g., need to recondition following harvesting), experiments are needed with such pipes. Given the potential effect of the connection method of the lead and copper pipes, experiments that use actual couplings used in replacements need to be performed. Again, there were advantages to using the end-to-end and externally wired connections in the projects discussed, but for relevance to partial LSL replacements there is no substitute for the actual couplings.
- **The impacts of both flow and stagnation should be evaluated.** While lead concentrations during flowing water (in a once-through configuration) are likely to be low given the short contact time of a parcel of water with the lead pipe, such flowing periods are important for replenishing the water in contact with the pipe with water that may promote scale development. While experiments need to include periods of flow, the lead concentrations will reach their highest concentrations following periods of stagnation, so sampling after such periods must also be included.
- **To examine the longevity of impacts of galvanic corrosion, long-term experiments are needed.** Lead release needs to be measured for a period of at least six months following the connection of representative aged lead pipes to new copper pipes using couplings that are used in practice. During this period, no other variables should be changed. To provide a study duration for galvanic effects that will be relevant to actual connections, a realistic regime of periods of flow and stagnation should be employed in such experiments.
- **Profiles of lead release along sections of lead pipe should be collected.** Both galvanic current and open circuit potentials indicate that the electrochemical impacts of galvanic corrosion are limited to the region nearest to the joint of the lead and copper pipes; however, the correlation of the localization of these measurements with lead concentrations should be examined. This can be done by collecting samples of lead from discrete sections of lead pipe following stagnation. Information about the localization and magnitude of lead release are critical to estimating the overall impact of galvanic corrosion on lead concentrations that might be observed at the tap. It is possible that even for relatively large sections of lead pipe that the higher lead release in the small zone closest to the junction with the copper pipe may dominate the total lead release to the water in the entire pipe section.
- **Replicate experiments are needed to provide statistical strength to conclusions.** Future experiments should be designed to include replicate experiments (duplicate or more) so that the random uncertainty associated with a particular type of pipe, water chemistry, or connection method can be accounted for when examining possible

differences in behavior among pipe type, water chemistry, and connection method. The need for replicate experiments will be particularly important when using aged lead pipes because different harvested lead pipes will have greater differences to one another than will different sections of new lead pipe.

- **All lead released from the pipes should be measured.** When pipe loops experiments are performed, lead concentrations should be measured both during flow and following prescribed stagnation periods. Reservoirs used for recirculation should be treated to dissolve all lead (with acid and also a reductant if lead(IV) oxides are suspected) that may have accumulated during recirculation. Dissolved lead as well as total lead should be measured to yield insights into the mechanisms of lead release associated with galvanic corrosion.
- **Lead concentration and electrochemical measurements should be integrated.** Measurements of both lead concentrations and electrochemical measurements are needed to simultaneously examine the degree of galvanic corrosion occurring (i.e. from current measurements) and the driving force for lead oxidation (potential measurements) and then relate that corrosion to observed lead release (from lead concentrations).
- **The aqueous phase and the pipe materials should both be characterized.** Whenever possible characterization of changes in the corrosion products in pipe scales should be combined with measurements of the aqueous phase. Solid phase characterization can identify which corrosion products form and where in relation to the galvanic connection they occur.

Many of these recommendations are being addressed in the companion set of laboratory and field experiments that are being performed as part of WaterRF Project #4349. Other investigations performed both by members of the research teams of Projects #3107, #4088, #4088b and by other researchers, have yielded additional insights relevant to these recommendations. Several of these studies are described in the following section.

## DISCUSSION OF RECENT RELATED STUDIES

In the time since the completion of the two projects just reviewed, several other studies have had their results published or presented. The findings of some of these additional studies and their relevance to partial LSL replacement are discussed below and summarized in Table 2.3.

### Study of Lead Release From Lead-Copper Couples for Different Flow Regimes

Two recent studies identified significant impacts of the method of providing flow through galvanically-coupled copper and lead pipes on lead release. The studies were performed under the supervision of Dr. Marc Edwards of Virginia Tech, the principal investigator for Report #4088b (*Galvanic Corrosion*). Both studies used externally wired connections. One study investigated the impacts of continuous versus intermittent recirculating flow on lead release, galvanic current and potential, and scale development (Arnold 2011). The other study used a once-through pipe rig system to examine lead release over a six-month period at three different sampling flow rates (Cartier et al. 2011). Both studies used triplicate experimental systems to provide strong measures of experimental uncertainty.

**Table 2.3**  
**Summary of Recent Studies Discussed other than the Three Focus Reports**

Title	Comments	Reference
New insights into lead and copper corrosion: Impacts of galvanic corrosion, flow pattern, potential reversal, and natural organic matter	Investigated continuous versus intermittent recirculating flow as well as the role of orthophosphate	Arnold 2011
Effect of flow rate and lead/copper pipe sequence on galvanic and deposition corrosion of lead pipe	Once-through pipe rig with three sampling flow rates	Cartier et al. 2011
Deposition corrosion of water distribution system materials	Copper addition to laboratory experiments with lead pipes	Clark, Hernandez, and Edwards. 2011
Lead contamination of drinking water after partial lead service line replacements with copper pipe: Bench testing of galvanic impacts	Use of different materials for connecting lead and copper and different distances when separated by an insulating spacer	Clark et al. 2011
Mineralogical evidence of galvanic corrosion in domestic drinking water pipes	Examination of metal-metal joints from actual installations	DeSantis, Welch, and Schock 2009
Contributions to drinking water lead from galvanized iron corrosion scales	Lead profile sampling in Washington, DC before and after lead service line replacements	McFadden et al. 2011
Lead occurrence and the impact of LSL replacement in a well buffered groundwater	Tap water in Guelph, Ontario following lead service line replacements	Muytwyk et al. 2009
Full versus partial lead service line replacement and lead release in a well buffered groundwater	Tap water in Guelph, Ontario following lead service line replacements	Muytwyk et al. 2009
The effect of partial lead service line replacements on lead leaching	Copper addition to laboratory experiments with lead pipes	Nguyen et al. 2009
Water quality effects of partial lead line replacement	Tap water sampling in Cincinnati, OH for homes with and without lead service line replacements	Swertfeger et al. 2006
Effects of flow and water chemistry on lead release rates from pipe scales	Laboratory study on effect of flow rate on lead release rate	Xie and Giammar 2011

Significant impacts of continuous versus intermittent flow on lead release from galvanically connected lead and copper pipes that received recirculating flow were identified in a recent laboratory investigation (Arnold 2011). Short (2-inch) new lead pipe sections were connected to copper pipe sections (12-inch) using externally wired connections and investigated for a range of water chemistry conditions. For evaluation of galvanic effects, the results from these experiments were compared with those from similar lead pipe sections connected to polyvinyl chloride (PVC) pipes. For pipe loops treated with either free chlorine or chloramine (and with concentrations maintained by daily adjustment) the corrosion current was initially higher in experiments with continuous flow than in those with intermittent flow, but the current for experiments with continuous flow gradually declined, and after 2-4 weeks of continuous recirculation the currents in systems with continuous flow were lower than those with intermittent flow. These results confirmed that passivation of lead pipes occurred faster and to a greater extent for continuous recirculation. The passivation with continuous flow and maintenance of free chlorine at a relatively high value of 4 mg/L  $\text{Cl}_2$  was so significant that the lead actually became cathodic relative to the copper; this observation was made based on reversal of both the current and the potential between the lead and copper pipes and by very low ( $< 1.5 \mu\text{g/L}$ ) lead concentrations once the reversal had occurred. This effect was attributed to the formation of  $\text{PbO}_2$  on the lead pipe surface. However, the passivating effect was reversible when the continuous flow was stopped; as the water stagnated, the free chlorine was depleted and then the lead that had accumulated in the  $\text{PbO}_2$  was released to yield very high (up to 130 mg/L) lead concentrations. Because of the passivation that occurred with continuous flow and the resulting decrease in the galvanic current, the total build-up of lead-containing scale on the pipes was greater for intermittent flow. Treatment of the reservoirs to mobilize any lead that had accumulated during 2-week cycles found that 40-85% of the total lead mobilized in the experiments could settle out in the reservoirs. This finding reinforces the importance of accounting for settled and adsorbed lead in recirculating pipe loop studies.

A separate study examined the impact of flow rate in a pipe rig system that comes closer to representing actual partial LSL replacement situations than most other studies (Cartier et al. 2011). Pipe rigs (10-ft lengths) received two short periods of flow and representative volumes each day in a once-through configuration for six months. Two types of lead-copper rigs were studied: one set of triplicate rigs had lead upstream of copper and the other triplicate set had copper upstream of lead, a system most relevant to partial LSL replacements. The behavior of these rigs was compared with that of a 10-ft rig that was entirely lead. After an initial stabilization period, which may have aided in development of pipe scales, samples for dissolved and total lead were collected following stagnation periods three times per week. At low flow rates that provided laminar flow, less lead was released from the lead-copper rigs than from the all-lead rig. The lead-copper rigs contained approximately 50% less lead than the all-lead rig, and galvanic corrosion was not sufficient to produce higher lead concentrations at low flow. The initial stabilization period and the twice daily inflow of new water could have promoted the formation of corrosion scales that limited lead release. Measurements of significant galvanic current (always greater than  $15 \mu\text{A}$ ) indicate that while lead release to the water may have been lower for the copper-lead rigs, galvanic corrosion was still occurring in those rigs and that the lead was accumulating in corrosion products instead of being released to the water. When the flow rates were then increased to two rates that represented turbulent flow, the baseline lead concentrations remained relatively stable but they were punctuated by spikes of much higher lead concentrations for the galvanically connected lead-copper rigs. The lead in these high

concentration spikes was almost entirely particulate, and these high concentrations are most likely caused by detachment of particles from the corrosion products whose development was promoted by galvanic corrosion. When the cumulative lead release over the entire 6-month period was calculated, the rigs with lead upstream of copper had released 30% less lead than the all-lead rig. However, there was no significant difference between the lead release from the all-lead rig and the copper-lead rig with copper upstream of lead (i.e., the configuration representative of a partial LSL replacement).

It has been proposed that copper placement upstream of lead pipe could result in deposition corrosion. In the process of deposition corrosion copper would deposit on the lead surface to form localized galvanic cells. Deposition corrosion of galvanized iron connected downstream of copper has often been observed (Cruse 1971). For copper connected to lead, Britton and Richards (1981) suggested that deposition corrosion may have been responsible for high lead concentrations observed in Glasgow, Scotland, but no direct observations of lead pipes that could have revealed copper deposits were attempted. It should be emphasized that neither the work of Cartier et al. nor that of Britton and Richards collected definitive evidence for deposition corrosion. Identification of copper deposits on the lead pipe surface would provide strong support for the operation of deposition corrosion, but neither study performed any characterization of pipe surfaces that could have confirmed or refuted the hypothesis that deposition corrosion plays a role in lead release. Addition of copper to water in lead pipes in laboratory experiments resulted in elevated lead releases in one case (Nguyen et al. 2009) but to no significant change in lead concentrations in another case (Clark, Hernandez, and Edwards 2011).

### **Impact of Water Chemistry on Galvanic Corrosion**

The same study that investigated continuous versus intermittent recirculating flow also made important observations regarding the impact of water chemistry on lead release from pipes that are galvanically connected to copper pipes (Arnold 2011). For pipe assemblies receiving recirculating flow, the addition of orthophosphate lowered lead concentrations for systems with chloramine but not for chlorine; with free chlorine the orthophosphate may have inhibited the development of the passivating  $\text{PbO}_2$  solid as has been reported previously (Lytle, Schock, and Scheckel 2009). However, in a 1-week stagnation period that followed the recirculating experiments, lower lead concentrations were present with orthophosphate present for both free chlorine and chloramine. Additional impacts of water chemistry were observed in other experiments using a static dump-and-fill approach, and a detailed discussion of those experiments is beyond the scope of this review. Those experiments observed corrosion currents and lead releases for galvanically coupled systems that were higher than those for unconnected lead pipes for the duration of the 3-month study, which is consistent with the non-passivating behavior observed in the static dump-and-fill experiments of Project #4088b (*Galvanic Corrosion*). The experiments found that (a) orthophosphate inhibited lead release for only one condition and actually increased it in some others and (b) the effects of galvanic corrosion were greater at low alkalinity. These observations highlight the impact of specific water chemistry on galvanic corrosion.

## Impact of Connection Type

A recent study used a static dump-and-fill experimental approach to investigate the effect of the connection method for lead and copper pipes (Clark et al. 2011); this study was led by the principal investigator of Report #4088b and used two waters in Blacksburg, VA and Montreal, Canada. Replacing an externally wired connection with a brass union slightly increased the resulting lead concentration, and the use of a brass corporation valve as a connector more significantly increased the lead release in both studies. The data are so recent that further interpretation is needed before drawing final conclusions, but the initial results suggest that the higher lead may come from the brass itself or from the exposure of both the internal and external walls of the lead pipe to the solution if a gap in the connection of the lead pipe to the coupling allows water to contact the outer wall of the lead pipe. Lower galvanic currents were actually measured with direct brass couplings than with the external couplings, which is in contrast to the higher lead concentrations measured. The use of couplings with insulating dielectric materials could shut down the galvanic current.

This same study also investigated the impact of the length of an insulating connector on the current through an external electrical connection of lead and copper pipes. In this case the distance measured is that of the insulating spacer and not the length along the lead pipe from the junction with the copper pipe as was done in previous studies. The current decreased consistently as the length of the spacer was increased. Such an observation could be caused by the increased distance over which ions must travel through the water to maintain charge balance; for galvanic corrosion the water acts as the electrolyte for the galvanic cell, and a large distance would lead to greater resistance to transport in such a cell. The results of this study are valuable in understanding the features of a connection that impact galvanic corrosion, but they may be of limited relevance to real world connections of lead pipe to copper tubing because connections using an insulating connector would probably not add any type of external connection.

## Investigation of Solid Phases in Harvested Joints of Dissimilar Metals

A recent study of solid phases near different metal-metal joints from used plumbing materials from four utilities provides information about galvanic corrosion that has occurred over long time periods (DeSantis, Welch, and Schock 2009). While the study investigated materials following long periods of use, it is inherently limited to examining the solid phases and does not provide information regarding current lead release or lead release over time. Using microphotography of cross sections of joints and X-ray diffraction analysis of solid phases scraped from pipe and fitting surfaces, the corrosion products could be examined. The study investigated lead pipes galvanically connected to brass from two different utilities. For one utility the joints had significant corrosion of the lead pipe to depths of 1-3 mm that were within the first few cm next to the joint. The observation is consistent with galvanic corrosion occurring in localized regions, and the results do not indicate any passivation of the zone. The authors further concluded that the solid phases observed near the joints indicate that the water in that local region had a lower pH than that of the bulk distribution system. However, for the other utility with lead-brass joints, the brass had actually corroded preferentially to the lead. The different corrosion behaviors of the lead-brass joints may be explained by significant differences in the distribution system water chemistry for the two utilities. The utility for which the brass corroded preferentially had orthophosphate added as a corrosion inhibitor (1.8-3.0 mg/L as  $\text{PO}_4$ ),

but the utility with preferential lead corrosion did not add orthophosphate; the orthophosphate could promote the formation of lead phosphate solids on the lead pipe that could inhibit its further corrosion. The utility with corrosion of the brass side of the joints also had a lower pH than the other utility and used monochloramine as the residual disinfectant while the other utility used free chlorine. A similar phenomenon of copper corroding preferentially to lead was observed for wiped joints of lead pipe connected to copper pipe from a third utility. This utility also had orthophosphate present, albeit at a much lower concentration (0.1-0.2 mg/L as  $\text{PO}_4$ ).

It should be noted that the observations of galvanic corrosion just discussed were for lead-brass and lead-copper connections using wiped joints. Wiped joints provide more direct contact of the dissimilar metals than will occur using compression fittings. Wiped joints are now rarely used, and current partial LSL replacements will employ compression fittings and not wiped joints. This same study did investigate one connection of lead pipe to copper pipe that was made with a brass fitting, and this sample showed minimal evidence of galvanic corrosion. This sample was from a different utility than those with the wiped joints that displayed galvanic corrosion of the lead, copper, or brass pipe. The lack of galvanic corrosion may be the result of a very high alkalinity (300 mg/L as  $\text{CaCO}_3$ ) for this utility and not the method of connection.

### **Monitoring of Tap Water Lead Concentrations following Partial Lead Service Line Replacements**

Studies of lead concentrations in tap water before and after both partial and full lead service replacements can potentially yield information regarding the impact of galvanic corrosion on lead release. Ideally such measurements can provide the best assessment of actual impacts of galvanic corrosion on lead concentrations; however, challenges in collecting samples (i.e., sampling the water from the service line and problems with resident-collected samples) and large variability from location to location have not allowed definitive conclusions to be reached. Further, the flow rate used during sampling can significantly affect the release of lead to the water (Britton and Richards 1981; Cartier et al. 2011; Xie and Giammar 2011); different flow rates were used among the various studies and some did not report the flow rate. A WaterRF project analyzed a compilation of data from multiple utilities conducting full or partial LSL replacements and concluded that full replacement was preferable to partial replacement. While partial replacement had either no significant benefit or only a small decrease in lead for the 2-month period after replacement, the lead concentrations had not increased significantly as would have been observed if galvanic corrosion had exacerbated lead release (Sandvig et al. 2008). Some results of individual utilities measurements are provided below.

In Guelph, Ontario intensive sampling over one year was performed on two homes that received full LSL replacements and two that received partial LSL replacements (Muytwyk et al. 2009). For both full LSL replacement sites the lead concentrations dropped dramatically. For partial LSL replacements very little decreases were seen in the first 1-2 months following replacement but after 6-9 months concentrations had decreased. A continuation of that decrease would indicate that disturbances following replacement, including galvanic corrosion, may passivate over time periods of several months and that the lead release may be transient albeit for several months. The sampling flow rate used in this study was not reported. A more recent investigation of data collected in Guelph from 2007-2010 confirmed the very significant decrease in lead concentrations following full LSL replacement for 286 full LSL replacements (Muytwyk et al. 2011). This study found much noisier results for lead following partial LSLs



(94 replacements tracked), high lead concentrations that persisted for at least 18 months, and some very high lead concentrations following some stagnation periods.

In the DC Water distribution system, a set of lead concentration profiles were collected before and after partial and also full LSL replacements (McFadden et al. 2011). Samples were collected at a flow rate of 2.5 L/min (0.66 gal/min). The study included four homes that were examined before replacement, after partial replacement, and also after full replacement. The collection of sampling profiles with both total and dissolved lead added strength to this study. For all four homes, after full replacement lead concentrations started on consistent decreasing trends, although there were spikes in concentrations for some homes immediately after replacement. Results were more varied following partial replacement. One site had essentially no change in lead concentrations, another had a clear decreasing trend, and two had milder decreases. By measurement of particulate and dissolved lead the authors suggested that some of the lead release may have been due to release of particulate lead that had accumulated in galvanized pipe corrosion scales downstream of the LSL. It is also possible that galvanic corrosion played some role in maintaining higher lead concentrations following partial replacement.

A study in Cincinnati examined lead concentrations for 21 homes that either received partial, full, or no LSL replacement in 1998-1999 (Swertfeger et al. 2006). Samples for total lead concentration were collected over the course of one year after the replacements and included both flushed and stagnated samples. Samples were collected by residents and then shipped to the utility's laboratory for analysis, and no flow rate was specified for sampling. The average lead concentration over the year after replacements was only slightly lower for partial replacements than for residences that retained their LSLs, and full replacements did result in much lower lead concentrations. The persistence of lead concentrations following partial LSL replacement was suggested by the authors to possibly be caused by galvanic corrosion; however, it should be noted that for none of the partial LSL replacements were concentrations significantly higher than before replacement. The sustained lead concentrations could also be due to release of particulate lead from galvanized pipe as was suggested by the DC Water study; however, no measurements dissolved lead were made that could be compared with total lead concentrations to check for the presence of particulate lead.

An earlier study in Glasgow, Scotland examined 186 households with LSLs (Britton and Richards 1981). For the subset of these for which pipe sequences of copper upstream of lead were present, due to partial service LSL replacement or other repairs, only 38% had lead concentrations considered satisfactory ( $< 0.1$  mg/L). In contrast, 89% of the households that did not have any copper-to-lead sequences had satisfactory lead concentrations. This study did not attempt to investigate households for any predetermined times following the insertion of copper upstream of the lead; consequently, the elevated lead release for many of these systems may have been a long-term phenomenon. Tap water samples were collected at a flow rate of 5 L/min. Profiles of lead concentrations in successive volumes of water collected from the tap also identified lead concentrations much higher for the region at the copper-lead junction than the region from the LSL. This observation provides further support for the impacts of galvanic corrosion being localized to the region closest to the lead-copper connection.

## SUMMARY AND CONCLUSIONS

The WaterRF projects that were the focus on this review yielded important findings regarding lead release following galvanic and non-galvanic corrosion. The projects had different objectives and consequently followed different research approaches. Project #3107 set out to investigate the effect of changing disinfectant on lead release. Project #4088 was focused on the impacts of chloride-to-sulfate mass ratio on lead release from lead-containing materials (principally leaded solder). Project #4088b then sought to more directly address the possibility of enhanced lead release due to galvanic corrosion. With respect to these primary objectives, the projects conducted experiments that generated data that satisfied these objectives.

The differences in research approaches between Projects #3107 and #4088b led to the reports reaching different conclusions regarding the potential for lead release associated with galvanic corrosion during partial LSL replacement. Project #3107 (*Changing Disinfectants*) concluded that galvanic corrosion could cause mild lead release and that the effect would be transient. Project #4088b (*Galvanic Corrosion*) concluded that galvanic corrosion would be more severe and that it could persist for much longer periods of time. The most significant differences in approaches that could have influenced the results were:

- **Different Stagnation and Flow Regimes.** The continuously recirculating flow in Project #3107 is ideal for the development of passivating pipe scales that could limit lead release associated with galvanic corrosion. In contrast, the long stagnation times and limited contact with freshly prepared water in the “dump-and-fill mode” experiments in Project #4088b presented a worst case scenario for lead release due to the development of local low pH regions, insufficient time and new water to promote scale development, and long stagnation times for lead accumulation.
- **Different Measurements of Lead Release.** The collection of samples from the recirculating reservoir of Project #3107 (*Changing Disinfectants*) did not allow measurement of all of the lead released from the pipes, so these measurements represent lower bounds on the total lead released. Project #4088b (*Galvanic Corrosion*) did measure all of the lead released.
- **Different Lead Pipe Materials.** Neither project used harvested aged pipes that would be most representative of those involved in actual partial LSL replacements. Starting with new lead pipe makes the issues of scale development all the more important.
- **Different Water Chemistry.** As directly acknowledged in the reports for both projects, galvanic corrosion and associated lead release are strongly dependent on water chemistry. Because each project studied waters with different compositions, differences are to be expected. Perhaps most significantly, Project #3107 employed periods of free chlorine that promote the development of  $\text{PbO}_2$ , which can be very effective in limiting galvanic corrosion and lead release; Project #4088b used monochloramine, which was depleted during stagnation times and even if it had been maintained would not have been capable of oxidizing lead to the +IV oxidation state to yield  $\text{PbO}_2$ .
- **Different Methods of Electrically Connecting Lead and Copper Pipes.** Project #3107 joined lead and copper pipes through a direct end-to-end connection and Project #4088 used an externally wired connection. In both projects the majority of galvanic corrosion was determined to occur in the region (within at most 6 inches) closest to the junction of the lead and copper pipes. However, measurements of open circuit potentials were

different for the two methods of making the connections; the impact of these differences on lead release was not assessed.

Additional research is needed to further explain the different observations of the projects and, more importantly, to generate data that can be used to estimate the contribution of galvanic corrosion to lead release following actual LSL replacements. Specific recommendations for future research are to:

- assess impacts on partial LSL replacement by using relevant pipes and connection methods.
- investigate lead release and corrosion under both flow and stagnant conditions.
- conduct long-term experiments at constant conditions to examine the longevity of the impacts of galvanic corrosion.
- collect profiles of lead release along sections of lead pipe.
- include replicate experiments in experimental designs.
- measure all lead released from pipes.
- integrate measurements of lead and copper concentrations with electrochemical measurements (both current and potential).
- characterize both the aqueous phase and the pipe materials.

Many of these recommendations have been incorporated in recent studies other than the three examined in this review. Taken together these studies highlight the importance of water chemistry, flow regime, and scale development on galvanic corrosion and lead release. Development of corrosion scales can effectively limit lead release to solution, although galvanic corrosion may still convert the lead metal of the pipe into lead(II) corrosion products that further accumulate at the surface. The development of corrosion products induced by galvanic corrosion can be susceptible to detachment depending on the flow of the water. The flow regime is further important because of the balance between flowing conditions providing fresh solution for development of scales and stagnant conditions resulting in the highest lead concentrations. Further research being conducted as part of this project is examining lead release from harvested and reconditioned lead pipes that are connected to new copper pipes using commercially available couplings.



## CHAPTER 3: BENCH-SCALE LABORATORY EXPERIMENTS

### OVERVIEW OF LABORATORY EXPERIMENTS WITH LEAD PIPES

#### Review of Galvanic Corrosion

The basic principle of galvanic corrosion is that when dissimilar metals with different electrochemical potentials are electrically connected and immersed in an electrolyte, a galvanic couple is set up that creates a driving force for oxidation-reduction reactions. The electrolyte provides a pathway for ion migration where metallic ions can move from the anode to the cathode, resulting in an acceleration of the anode corrosion. As described previously in Chapter 2, after PLSLRs a lead pipe connected to copper tubing can be a galvanic couple with the lead serving as the anode (i.e., the portion of the couple that gets oxidized). Electrons released by lead oxidation can travel through the electrically-connected system to the copper tubing where a reduction reaction occurs; the reduction reaction may involve reduction of dissolved oxygen ( $O_2(aq)$ ) to water on the copper surface or other reactions. The net reaction of the galvanic reaction is shown in equation 3.1.



This net reaction accelerates oxidation of the elemental lead in the lead pipe, and the resulting  $Pb^{2+}$  can be released to the water and increase the lead concentration. It should be noted that buried lead service lines generally have internal wall scales of corrosion products that contain lead(II), and a portion of the lead(II) generated by galvanic corrosion may accumulate during growth of these corrosion products and not be released to the water. As discussed in the preceding chapter, different laboratory experiments have reached different conclusions regarding the duration and severity of galvanic corrosion.

#### Overview of Experimental Approach

A set of new laboratory experiments were performed at Washington University in St. Louis to examine the impacts of different connection methods and water chemistry on lead release associated with galvanic corrosion of lead pipes connected to copper tubing. These experiments were performed with lead pipe sections harvested from service lines in Providence, RI, and Washington, DC, and with commercially available couplings. The primary objective of the experiments was to examine the extent of galvanic corrosion associated with the connections, and while the experiments provide some information regarding the duration of the effects, the issue of duration is best addressed in the experiments performed at the Fort Reno Water Quality Office and described in Chapter 4.

Harvested lead pipes were used because they have intact pipe scales that may affect the response of the pipe to galvanic corrosion. By measuring the surface potential, Reiber and Dufresne (2006) found that while galvanic corrosion was significant on new lead pipe surfaces, it was minimal and highly transient on aged lead pipes. For a system in which new lead pipe and copper tubing were galvanically connected, Arnold (2011) observed that lead(IV) oxides formed on lead pipes after approximately two months of continuously recirculation with chlorinated

**Table 3.1**  
**Connection methods used for different systems**

Pipe Type	Coupling Type				
	Brass compression	Brass dielectric	Plastic	Plastic with external wire	Low-lead brass
PVC pipe (Control)	X	X	X		X
DC lead pipe	X	X	X	X	X
Providence lead pipe	X		X		X

water and that the presence of the lead(IV) oxides protected the lead pipes from galvanic corrosion. Although corrosion products may passivate the pipe surface, they may break off and be released as particulate lead at high flow rates (Cartier et al, 2012). Consequently, measurements of both total and dissolved lead were important to this study. While new or cleaned lead pipes were commonly used in previous work to simulate PLSLRs (Giammar et al. 2009; Clark et al. 2011), only a few studies have used lead pipes harvested from actual distribution systems (Cartier 2012).

Five different connection methods were studied to examine lead release from pipes connected to copper tubing (Table 3.1). These included connections made using four different couplings: standard brass, brass dielectric, all-plastic polypropylene, and low-lead brass. The inclusion of low-lead brass was motivated by recent federal legislation (Reduction of lead in drinking water act, PL 111-380) that specified that the lead content for water distribution and plumbing wetted components (or the weighted average of the wetted components of an individual assembled product) will be limited to not more than 0.25% by weight effective January 2014. This is a reduction from the current content limits of 8.0% for water distribution system components, and 4.0% for plumbing components permitted under the Safe Drinking Water Act. A fifth connection method involved the connection of copper and lead with a plastic coupling and then an external wire to allow electrical conductivity between the two materials. The use of external wires to initiate galvanic corrosion was previously observed to increase lead release by 1.5 to 75 times in stagnant water (Triantafyllidou and Edwards 2011). This connection method allows direct measurement of galvanic currents by placement of a multimeter in the externally-wired connection.

Experiments used a flow regime that included periods of recirculating flow with intermittent stagnation periods. This approach was followed to allow the preparation of reasonable volumes of water in the laboratory in St. Louis to simulate the composition of water in Providence of Washington, DC. Stagnation periods were included because these were expected to result in the highest lead concentrations and are also most relevant to protocols for monitoring compliance with the Lead and Copper Rule. Flow periods were included because these are important for allowing the development of pipe scales that may passivate the pipe surface.

Water chemistry was a final factor evaluated with respect to its effect on galvanic corrosion. Experiments with Providence pipes examined the possible benefits of orthophosphate addition on lead release for the relatively high pH of water in the Providence distribution system. Orthophosphate is often added to inhibit lead corrosion (McNeill and Edwards 2002), but previous studies did not find it to decrease lead release from galvanic corrosion (Cartier 2012; Cartier et al. 2012). The experiments with Washington, DC pipes examined the impacts of

increasing the chloride-to-sulfate mass ratio (CSMR) and decreasing the total dissolved solids (TDS). Several studies have reported that increasing the chloride-to-sulfate mass ratio (CSMR) accelerated lead release due to galvanic corrosion (Nguyen et al. 2010; Triantafyllidou and Edwards 2011), and the critical range above which lead release was enhanced was 0.6 to 0.77 (Edwards, Jacobs, and Dodrill 1999; Nguyen, Stone, and Edwards 2011).

### **Timeline of Experiments**

The laboratory experiments were performed over the course of two years. Before examining any impacts of connection methods or water chemistry, individual pipes were conditioned in the laboratory to allow them to stabilize from any effects associated with harvesting, shipment or storage. Conditioning was performed in both static dump-and-fill modes and a recirculating flow mode. A laboratory apparatus was available for experiments with recirculating flow that could accommodate four pipe assemblies at a time. To optimally use the apparatus and manage the overall workload over the course of the project, experiments were performed according to the schedules in Table 3.2 (Providence) and Table 3.3 (Washington, DC).

## **MATERIALS AND METHODS**

### **Materials**

Aged lead pipes were harvested from the Providence, RI and Washington, DC distribution systems and shipped to Washington University in St. Louis for laboratory experiments. At the time of pipe harvesting, moist sponges were inserted into the pipes before their ends were tightly sealed with tape to prevent the dehydration of the pipe scales. The pipes did not contain free water after harvesting. When the pipes were received in the laboratory the scales appeared to be physically intact. Pipes were given identification codes based on their harvesting address; pipes that have the same first digit were from the same location. Eight lead pipes were received from Providence (Table 3.4). The pipes had been in use for 80 to 110 years. The pipes had inner diameters of 0.625 inch and outer diameters of 1.188 inch. Eight pipes that had been in use for over 100 years were received from Washington, DC (Table 3.5). The Washington DC pipes had inner diameters of 0.75 inch and outer diameters of 1.18 to 1.2 inch. All pipes were cut to generate 24-inch sections for use in experiments. Cutting was performed using a bandsaw to minimize deformation of the pipe cross-section during cutting. After the cuts were made, the pipe ends were visually examined and there was no visible evidence of pipe scale disruption.

Type K copper tubing with inner diameters of 1 inch and outer diameters of 1.125 inches was cut to 24-inch sections (McMaster-Carr). Polyvinyl chloride (PVC) pipe sections (1 inch) (McMaster-Carr) with 24-inch lengths were used in control experiments (i.e., without lead pipe) with all couplings except those with the low-lead brass couplings. The control experiments that were conducted with the low-lead brass couplings used chlorinated polyvinyl chloride (CPVC) pipe (McMaster-Carr). Couplings donated for use in the experiments were brass compression fittings (A.Y. McDonald), low-lead brass compression fittings (A.Y. McDonald), brass dielectric fittings (A.Y. McDonald) and an all-plastic polypropylene fittings (Harco - Philmac). (See Chapter 4 for further characterization of the brass compression fittings.) Reagent grade

**Table 3.2**  
**Timeline of the experiments conducted in the recirculating flow mode using Providence pipes**

Coupling Type <sup>1</sup>	Experimental Dates			
	4/04/2011 – 5/09/2011 (5 weeks)	5/09/2011 – 6/20/2011 (6 weeks)	5/07/2012 – 5/28/2012 (3 weeks)	5/28/2012 – 7/09/2012 (6 weeks)
Plastic	Conditioning of lead pipe	Connected to Cu tubing (no orthophosphate)		
Brass	Conditioning of lead pipe	Connected to Cu tubing (no orthophosphate)		
Low-lead Brass			Conditioning of lead pipe	Connected to Cu tubing (no orthophosphate)
Low-lead Brass			Conditioning of lead pipe	Connected to Cu tubing (with orthophosphate)

<sup>1</sup>Experiments were conducted in duplicates.



**Table 3.3**  
**Timeline of the experiments conducted in the recirculating flow mode using Washington, DC pipes**

Coupling Type <sup>1</sup>	Experimental Dates							
	8/29/2011 – 9/26/2011 (4 weeks)	9/26/2011 – 11/07/2011 1 (6 weeks)	11/07/2011 – 12/05/2011 (4 weeks)	12/05/2011 – 1/02/2012 (4 weeks)	1/02/2012 – 2/13/2012 (6 weeks)	2/13/2012 – 2/20/2012 (1 week)	2/27/2012 – 3/19/2012 (3 weeks)	3/19/2012 – 4/30/2012 (6 weeks)
Plastic with and without external wire	Conditioning of lead pipe	No wire CSMR = 0.7	No wire CSMR = 7.0	No wire CSMR = 0.7	No wire CSMR = 0.7	No wire CSMR = 0.7		
Brass	Conditioning of lead pipe	CSMR = 0.7	CSMR = 7.0					
Brass Dielectric				Conditioning of lead pipe	CSMR = 0.7			
Low-lead Brass <sup>2</sup>							Conditioning of lead pipe	CSMR = 0.7

<sup>1</sup>Experiments were conducted in duplicates.

<sup>2</sup>After April 30, 2012, the lead and copper pipe assemblies were stored in a connected state with daily replacement of water through a dump-and-fill mode, and they were then used to investigate the effects of TDS in the recirculating flow mode for five weeks starting on August 3, 2012.

**Table 3.4**  
**Lead Pipes from Providence Water used in this study**

Pipe No. <sup>1</sup>	O.D. (in)	Age (Yr)
1A	1.188	101
1B	1.188	
2A	1.188	113
2B	1.188	
8A	1.188	80
8B	1.188	
9A	1.188	90
9B	1.188	

<sup>1</sup> Pipes with the same number are from a service line serving a single address.

**Table 3.5**  
**Lead Pipes from D.C. Water used in this study**

Pipe No. <sup>1</sup>	O.D. (in)	Age (Yr)
1	1.20	108
2a	1.20	105
2b	1.20	105
3a	1.20	110
4a	1.18	110
4b	1.18	110
4c	1.18	110
4e	1.18	110

<sup>1</sup> Pipes with the same number are from a service line serving a single address.

chemicals CaCl<sub>2</sub>, MgCl<sub>2</sub>, MgSO<sub>4</sub>, Na<sub>2</sub>HPO<sub>4</sub>, NaF, NaCl, NaHCO<sub>3</sub>, NaOCl solution, NaOH, and HNO<sub>3</sub> (Fisher Scientific) and ultrapure water (resistivity > 18.2 MΩ-cm) were used to synthesize experimental tap water used in the experiments.

### Pipe Conditioning

Before connecting the lead pipes to the copper pipes, the lead pipes were reconditioned with water prepared to simulate the chemistry of the Providence (Table 3.6) or Washington, DC (Table 3.7) distribution system. The goal of conditioning was to achieve stable lead release from the pipes prior to making the connections to the copper tubing so that any effects of the connections could be clearly seen. The pipes were first conditioned in a static “dump-and-fill” mode and then in a system with periodic recirculating flow. Conditioning was also performed when pipes used in early experiments were used again for subsequent experiments; this was done for Providence pipes when the effect of orthophosphate was investigated.

**Table 3.6**  
**Water composition of synthetic Providence water**

Water composition parameter	Target range	Actual value <sup>1</sup>
pH	9.5 to 9.9	9.6 to 9.8
Free residual chlorine, mg/L as Cl <sub>2</sub>	0.16 to 0.50	0.42
Total alkalinity, mg/L as CaCO <sub>3</sub>	9.3 to 16.3	12.0
TDS, mg/L	97 to 113	113
Total hardness, mg/L as CaCO <sub>3</sub>	34.3 to 44	38.5
Chloride, mg/L	17.3 to 22.4	19.4
Sulfate, mg/L	20.0 to 24.0	21.8

<sup>1</sup> The actual value of the pH was determined from daily measurements, and the actual values for the other parameters were set at these concentrations by the preparation of the synthetic Providence water.

**Table 3.7**  
**Water composition of synthetic Washington, DC, water**

Water composition parameter	Target range <sup>1</sup>	Actual value	Actual value	
			with elevated CSMR	with low TDS
pH	7.7 to 7.8	7.7	7.7	7.7
Total chlorine, mg/L as Cl <sub>2</sub>	3.6 to 3.8	3.7	3.7	3.7
Total alkalinity, mg/L as CaCO <sub>3</sub>	49 to 99	76	76	76
TDS, mg/L	126 to 261	310	310	180
Total hardness, mg/L as CaCO <sub>3</sub>	114 to 155	128	128	43
Chloride, mg/L	30 to 56	34	77	10
Sulfate, mg/L	40 to 71	50	11	15
Orthophosphate, mg/L as PO <sub>4</sub>	2.4 to 2.8	2.5	2.5	2.5

<sup>1</sup> The ranges are for the Dalecarlia Water Treatment Plant

This “dump-and-fill” mode was operated on a daily cycle during weekdays for eight weeks or more. Freshly prepared synthetic distribution system water was fed into the pipes using a peristaltic pump (Masterflex L/S, Cole Parmer, model number 7554-80) and then allowed to sit stagnant for 24 hours during weekdays and 72 hours over the weekend. After the prescribed stagnation period, the water was dumped from the pipes by opening valves that had sealed off the pipe and holding the pipe vertically. Holding the pipe vertically and not just allowing it to drain by gravity from its slightly inclined position resulted in more observable release of particulate during the first weeks of conditioning. The pipes were then refilled to start a new stagnation period. During the first five weeks, 10-mL samples were collected from the dumped water on Tuesdays and Fridays and acidified to 2% HNO<sub>3</sub> to preserve the samples prior to total lead analysis. Starting in Week 6, 20-mL volumes were collected once or twice a week on weekdays, and 10 mL of this water was filtered with a 0.45 µm polyethersulfone (PES) syringe filter and acidified to 2% HNO<sub>3</sub> in preparation for dissolved lead analysis. The remaining 10 mL was acidified to 2% HNO<sub>3</sub> and preserved for total lead analysis. The dumped water that was not collected for lead analyses was used for the measurement of pH and total chlorine concentration.

After being conditioned in the static mode, specific pipes were selected for further conditioning in a recirculating flow mode. These pipes were selected because they demonstrated the greatest stability in lead concentrations during static conditioning and had the lowest pipe-to-pipe variability. Conditioning with periodic recirculating flow was conducted for four or more weeks. In this process, the pipes were conditioned in a similar configuration used in experiments with connections of the lead pipes to the copper tubing (Figure 3.1). A 10-L polyethylene reservoir was used as the source and sink of the water flowing through the pipe. A peristaltic pump (Masterflex I/P, Cole Parmer, model number 77601-00) was used to provide and control the flow rate. A variable area flow meter (Blue-White F-400, Cole Parmer) was used to monitor the flow rate. Three-way valves were positioned at the upstream and downstream ends of the pipes for collection of samples. Flexible plastic tubing (Tygon ®) was used to provide flow from the reservoirs through the pump to the pipe assemblies and then from the exit of the pipe assemblies back to the reservoirs. Both during conditioning and after being connected to copper tubing, the pipe assemblies were fixed in a metal rack that held them in a slightly inclined position (lead above copper) with an angle of approximately 15°. The inclined position allowed the pipes to remain completely filled with water and prevented the presence of any air bubbles in the pipe assemblies.

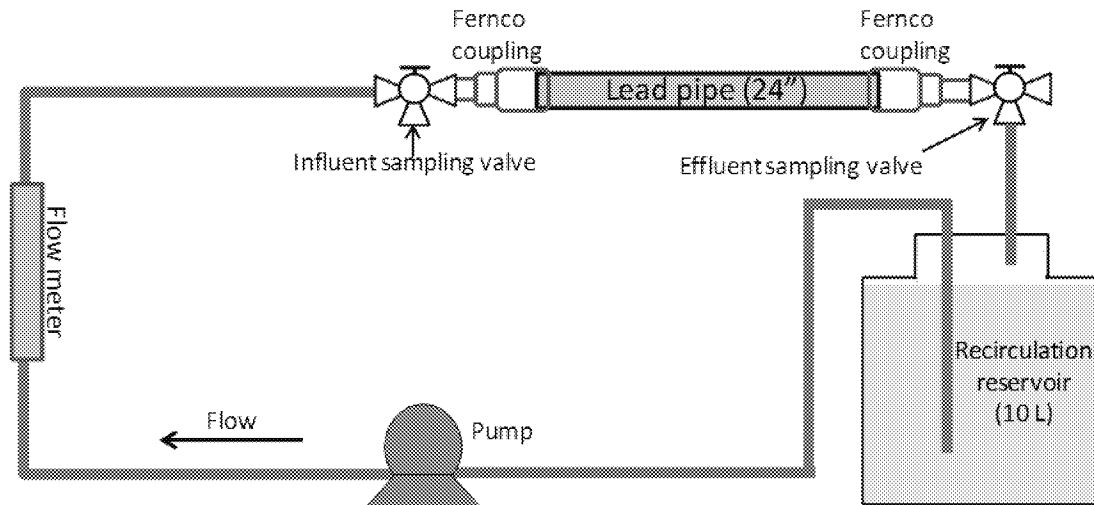
The system was operated on a daily cycle during the weekdays (Figure 3.2). On each Monday morning, freshly made synthetic distribution system water was fed into the pipes from the reservoirs. The weekday cycle for Monday through Thursday began with a 6-h stagnation time that was followed by 15 minutes of flow, a 17.25-h stagnation period, and finally 30 minutes of flow. On Fridays, the 17.25-h stagnation period was replaced with a 65.25-h stagnation period (over the weekend), hereafter just referred to as the 65-h stagnation period, as the last phase of the weekly cycle. The reservoirs were then replaced with cleaned ones with freshly made feed solutions to start the next week's cycle. Flow and stagnation were controlled by turning the pumps on and off. The flow velocity during recirculation was 1 ft/s (5.2 L/min). The total chlorine concentration in the reservoir was monitored and adjusted to the target value regularly. Adjustment of the chlorine concentration did not affect the pH because sufficient buffering was available in both synthetic waters that were prepared.

The influent was sampled each Monday, Wednesday, and Friday before the 6-h stagnation period and on Friday before the 65-h stagnation period. Influent sampling involved opening the valve on the upstream end of the pipe and collecting a 50-mL sample at a flow rate of 1 L/min. Following the stagnation periods, 50-mL effluent samples were collected at a flow rate of 1 L/min by opening the sampling valve on the downstream end of the pipes.

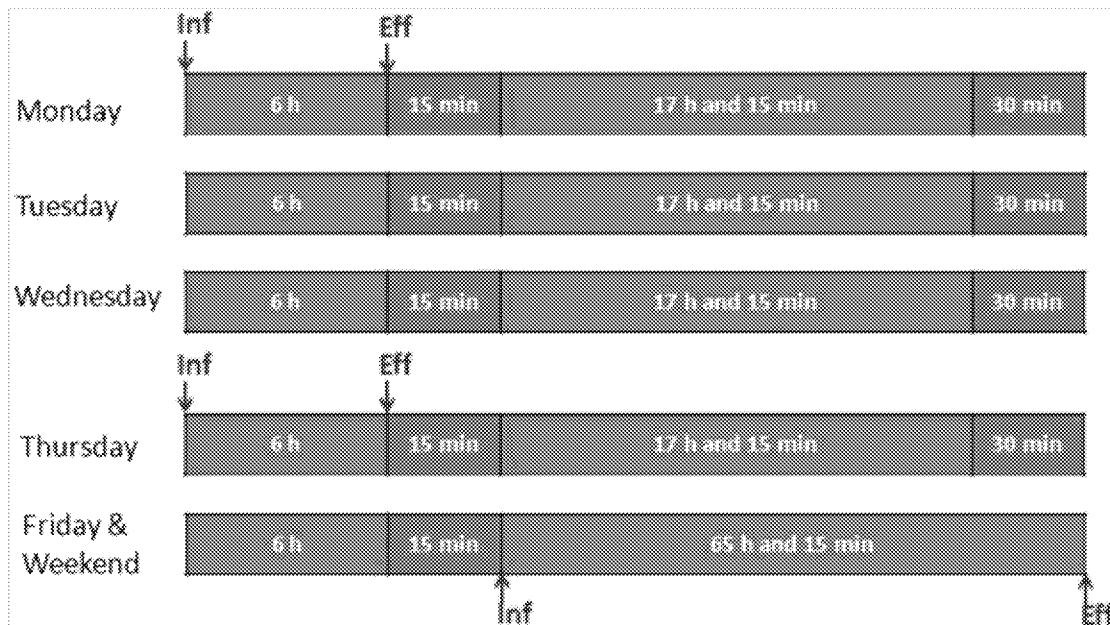
From the 50 mL of water collected, 10 mL were acidified to 2% HNO<sub>3</sub> for total lead analysis, 10 mL were filtered (0.45 µm PES syringe filter) and then acidified to 2% HNO<sub>3</sub> for dissolved lead analysis, and the remaining 30 mL were used for pH and total chlorine measurement. Orthophosphate concentration was also determined for selected samples.

### **Control Experiments With Couplings**

To test for lead release from the couplings and potential unexpected sources, control experiments were performed using PVC pipes connected to copper tubing with the couplings then studied in experiments with lead pipes. The experiments used the synthetic distribution system water. Experiments with synthetic Providence water were performed with one brass compression coupling and one plastic coupling. Brass, brass dielectric, low-lead brass, and



**Figure 3.1** System for pipe conditioning in the recirculating flow mode



**Figure 3.2** Sampling times and flow cycle used for pipe assemblies. The gray sections (6 h, 17 h and 15 min, and 65 h and 15 min) are periods of stagnation, and the blue sections (15 min and 30 min) denote periods of recirculating flow. ‘Inf’ indicates collection of a sample collected at the influent sampling port before stagnation, and ‘Eff’ denotes the sample collected in the effluent sampling port after stagnation.

plastic couplings were evaluated using the synthetic Washington, DC, water. Because these experiments did not include a lead pipe section, the only significant source of lead should be the brass couplings. Experiments were operated for four weeks using the same weekly cycle used for the experiments with connected lead and copper pipe assemblies. To further distinguish lead release from the low-lead brass couplings from other unexpected sources, like plastic tubing or

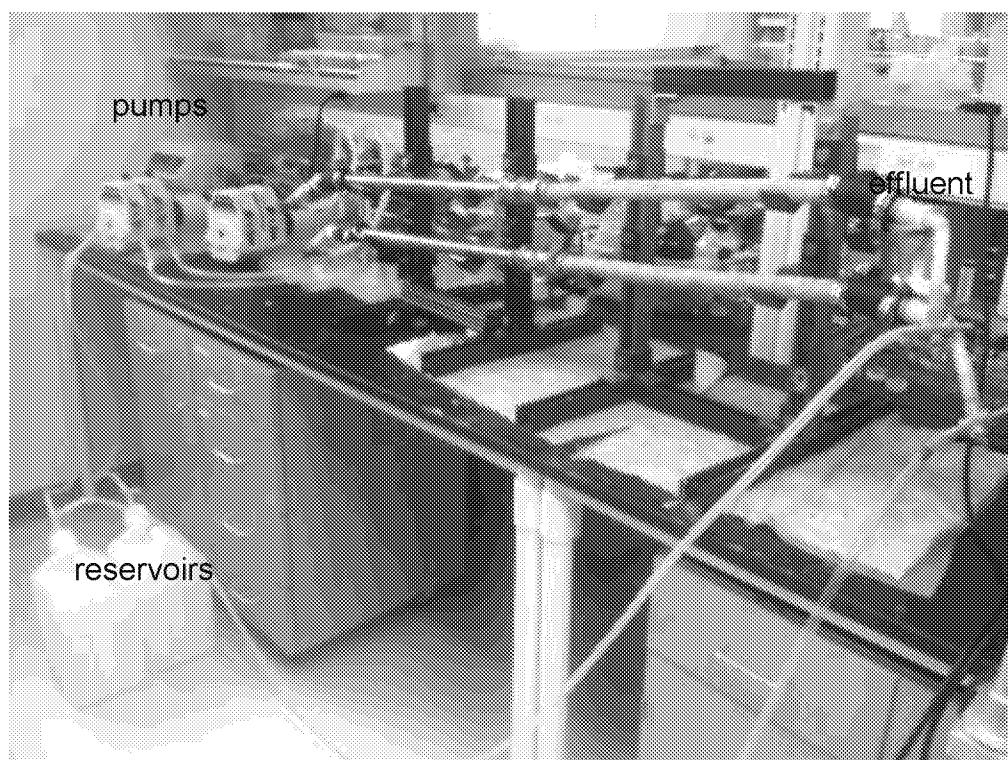
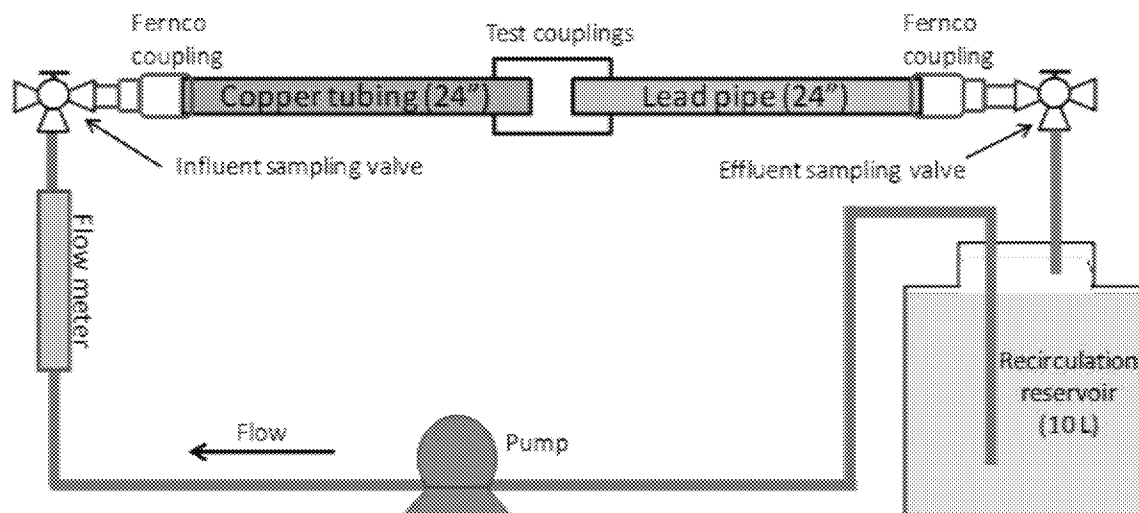
valves, for the low-lead brass-coupled Cu-CPVC pipe assemblies, the low-lead brass couplings were bypassed during one week of the experiment. Each experimental condition was run in duplicate.

### **Connection of Lead Pipes to Copper Tubing**

After conditioning in the recirculating flow mode, the lead pipes were connected to copper tubing using the different coupling types and placed in a recirculation system (Figure 3.3) similar to that used for conditioning. As noted earlier Providence pipes were examined using brass and plastic couplings while Washington pipes were also evaluated with brass dielectric and low-lead brass couplings as well as with the plastic couplings and an external wire (Figure 3.4). This connection was made for the same pipes that had been studied with the plastic couplings (without the externally wired connection) at first with the original CSMR and then at an elevated value (discussed below). Before making the connection with the external wires, the pipes were reconditioned in the recirculating mode using the water with the original CSMR for four weeks. The pipe assemblies were then operated with the external connection for six weeks. This connection method is similar to that used in Project #4088b (*Galvanic Corrosion*). In addition to enabling galvanic corrosion, it also allows for the measurement of galvanic current by placing a current meter in the external wire connection.

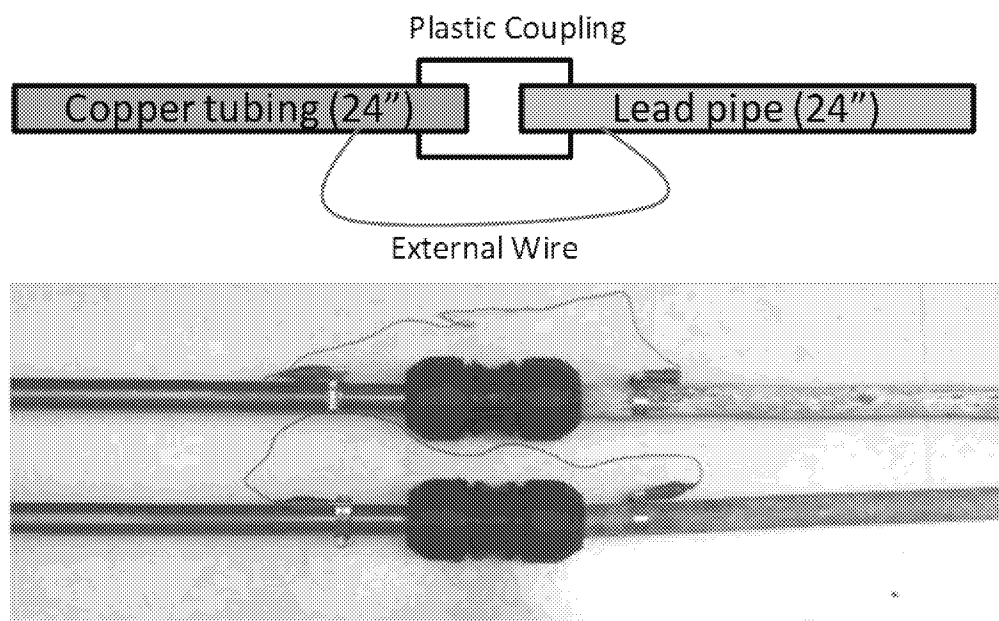
Only the brass compression couplings provide an electrical connection between the copper and the lead; however, the brass dielectric couplings do have the potential for dissimilar metal couples of copper/brass and brass/lead. Electrical continuity between the lead pipe and copper tubing was tested by measuring the electrical resistance between the two metals with a digital multimeter. As expected there was essentially no resistance for the pipe assemblies using the conventional brass couplings, low-lead brass couplings, or plastic couplings with an externally wired connection. The resistance was very high (off scale) for the assemblies that used the plastic and brass dielectric couplings. The internal volumes of the lead pipe and copper tubing sections were 180 mL and 310 mL, respectively. Experiments were operated in a recirculation mode with intermittent stagnation periods according to the same cycle used for recirculation and described in the preceding section. Experiments were conducted for six weeks.

In both the experimental lead-copper and control PVC-copper experiments, influent samples of 50 mL were collected at a flow rate of 1 L/min on each Monday and Thursday before the 6-h stagnation period and on Friday before the 65-h stagnation period. Influent samples were collected at the point where water entered the pipe assemblies. For the 6-h stagnation period on Mondays the influent came directly from the freshly prepared water in the reservoir and this water had not yet been in contact with any of the pipes, and for the 6-h Thursday stagnation period and the 65-h stagnation period the influent sample came from a reservoir that contained water that had previously been in contact with the lead pipes during earlier stagnation and recirculation periods of that week. Although these influent samples will contain some lead, by comparison with the effluent from the pipes after the prescribed stagnation period, the extent of lead contributed to the water during stagnation can be determined. Effluent samples of approximately 500 mL were collected at a flow rate of 1 L/min following the Monday and Thursday 6-h stagnation periods and the weekend 65-h stagnation period. A profile sampling approach was performed once for each lead-copper pipe assembly during the six weeks of the experiments. In this approach, seven consecutive 70-mL samples were collected for each lead-copper pipe assembly after 6-h stagnation, in an effort to identify possible localization of lead



**Figure 3.3** Experimental system with lead pipes and copper tubing connected with plastic, brass, brass dielectric or external galvanic wired plastic couplings. The system is shown as a schematic (top) and with a photograph of the actual system in the laboratory.

release along the pipe sections. For each sample, 10 mL was used for total lead and copper analysis, 10 mL for dissolved lead and copper, and the remaining volume (30 mL for most samples and 50 mL for the samples from the profile sampling) for pH and total chlorine measurement. The concentration of orthophosphate was also measured for selected samples.



**Figure 3.4 Connections of lead pipe to copper tubing by plastic couplings with external galvanic wires: (a) schematic view and (b) photograph of experimental set-up**

After replacing the old reservoir with a new one each Monday, the solution in the old reservoir was acidified to  $\text{pH} < 3$  by addition of concentrated  $\text{HNO}_3$  and allowed to sit at this low pH for at least 24 hours before collecting a 10-mL sample for total lead and copper analysis. This acidification was intended to mobilize and dissolve particulate or adsorbed lead that had accumulated in the reservoirs during the previous week of recirculating flow periods.

To determine whether the chloride-to-sulfate-mass-ratio (CSMR) would affect galvanic corrosion, after six weeks of the experiment pipes with plastic and brass compression couplings were exposed to synthetic DC water with elevated CSMR for four weeks (Table 3.7). The CSMR was increased from an initial value of 0.7 to an elevated value of 7.0. The value of 0.7 is near the boundary of where CSMR was found to result in enhanced galvanic corrosion in previous research, and the value of 7.0 is well above that threshold (Nguyen, Stone, and Edwards 2011).

The effect of total dissolved solids (TDS) on lead release was determined using the DC pipes with low-lead brass couplings. After six weeks of the experiments with the original TDS (310 mg/L), the lead-copper pipe assemblies were stored in a static “dump-and-fill” mode for three months. Then the pipe assemblies were placed in the recirculating apparatus with a low-TDS synthetic DC water ( $\text{TDS} = 180 \text{ mg/L}$ ) (Table 3.7). After four weeks of the experiments using the low TDS water, the TDS was adjusted to its original value and experiments were run for an additional week.

The effect of orthophosphate on lead release associated with galvanic corrosion was investigated using pipes from Providence, RI. After being conditioned in the recirculating flow mode for three weeks, the lead pipes were connected to copper tubing using the low-lead brass couplings and kept in the same recirculation system used for conditioning. At the time of the connection, two pipes (1A and 2B) were exposed to water with orthophosphate at a concentration of 2.5 mg/L as  $\text{PO}_4$ , and these two assemblies are referred to as OP-1 and OP-2. This concentration was selected because it is within the range used for corrosion control and it is



the same concentration used in our previous experiments with pipes from Washington, DC. A stock solution of  $\text{Na}_2\text{HPO}_4$  was used as the source of phosphate. No orthophosphate was added to the other two pipe assemblies (Pipe 9A and 1B), which are referred to as C-1 and C-2.

### Characterization of Corrosion Products

The as-received pipes were characterized with respect to the composition and structure of the corrosion products. Portions of these pipes were cut longitudinally and scales were scraped from the inner surface of the pipes using a small metal spatula. The scales were analyzed by XRD to identify crystalline solid phases present in the pipe scales. The morphology and semi-quantitative elemental composition of the corrosion products were determined by scanning electron microscopy (SEM) with energy dispersive X-ray analysis (EDX). The elemental composition was further quantified by digesting 0.03 g of the scale in a mixture of 10 mL concentrated  $\text{HNO}_3$  and 2.5 mL concentrated  $\text{HCl}$  that was heated at  $100^\circ\text{C}$  for 4 hours (Environmental Express Hot Block). The digestate was then diluted to 50 mL with ultrapure water and centrifuged for 10 min at 15000 relative centrifugal force (RCF). A 10 mL aliquot of the supernatant was collected, filtered using a  $0.22\ \mu\text{m}$  PES syringe filter, and preserved for elemental analysis.

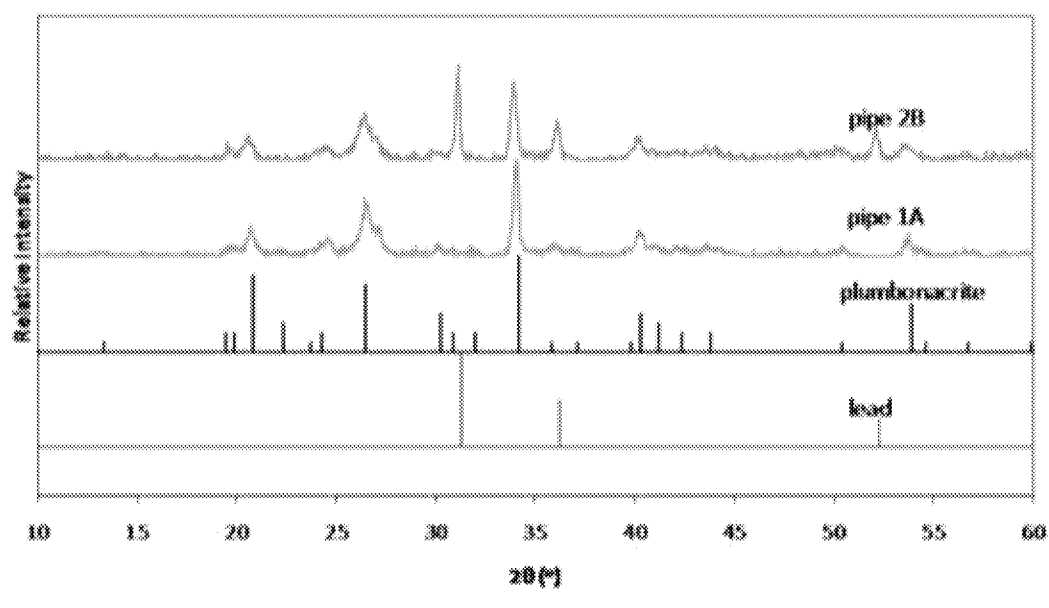
### Analysis Methods

Total and dissolved concentrations of lead and copper were measured by inductively coupled plasma mass spectroscopy (ICP-MS) (Agilent 7500ce). XRD was performed on a Rigaku Geigerflex D-MAX/A diffractometer using Cu-K $\alpha$  radiation. Total chlorine and orthophosphate concentrations were determined by the standard DPD and ascorbic acid colorimetric methods (4500-Cl G and 4500-P E) with a spectrophotometer (PerkinElmer Lambda XLS+), respectively. Orthophosphate was measured for selected samples by the ascorbic acid colorimetric method (4500-P E). Solution pH was measured with a glass pH electrode and pH meter (Accumet).

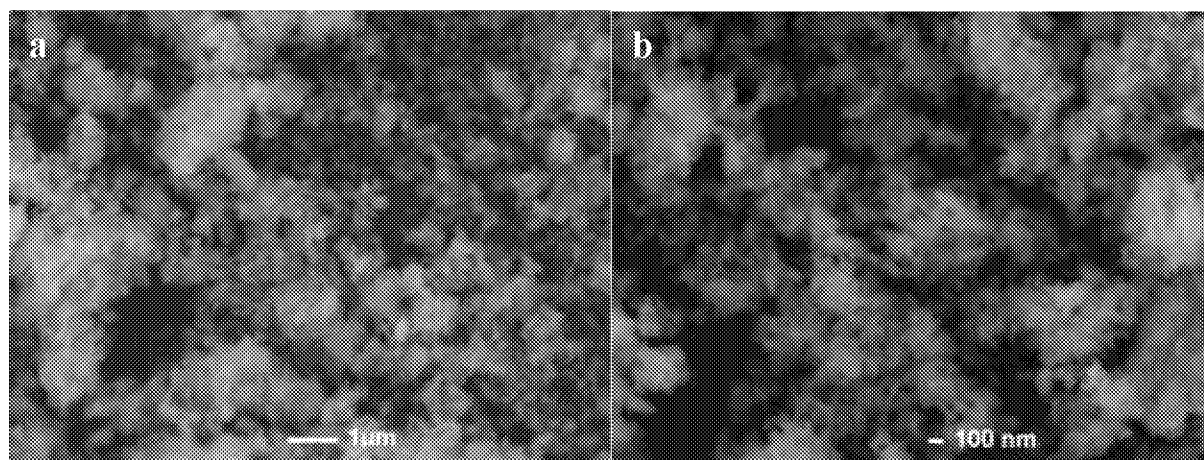
## EXPERIMENTS WITH PIPES FROM PROVIDENCE, RI

### Characterization of Corrosion Products

The pipe scales scraped from Pipes 1A and 2B prior to conditioning were white powders. XRD patterns (Figure 3.5) showed that the dominant crystalline phase in the scales of both pipes was the lead(II) hydroxycarbonate plumbonacrite ( $\text{Pb}_{10}(\text{CO}_3)_6(\text{OH})_6\text{O}$ ). The lead(II) carbonate cerussite ( $\text{PbCO}_3$ ) and the hydroxycarbonate hydrocerussite ( $\text{Pb}_5(\text{CO}_3)_3(\text{OH})_2$ ) are more frequently observed lead(II) solids in pipe scales from previous studies, and plumbonacrite is a less common corrosion product. The formation of plumbonacrite instead of other lead(II)-containing solids might be due to the water chemistry in the Providence drinking water distribution system. The water has a high pH with a relatively low alkalinity, which can favor more hydroxide-rich solids. For comparison a utility with a similarly high pH (9.0-9.5) but a higher alkalinity (about 40 mg/L as  $\text{CaCO}_3$ ) had scales that were dominated by the more carbonate-rich solid hydrocerussite. Although free chlorine was used as the disinfectant, a strong



**Figure 3.5** X-ray diffraction patterns of the crystalline phases in the scales from Providence pipes. Powder diffraction file patterns for plumbonacrite ( $\text{Pb}_{10}(\text{CO}_3)_6(\text{OH})_{10}\text{O}$ ) (00-019-0680) and elemental lead (01-071-3758) from the International Centre for Diffraction Data are shown for reference.



**Figure 3.6** Electron micrographs of the corrosion scales from Pipe 1A from Providence. Panel “b” is a higher magnification image of a section from panel “a”.

enough oxidant to produce lead(IV) oxides ( $\text{PbO}_2$ ) in some distribution systems, no lead(IV) oxide was observed in the Providence pipes based on the XRD pattern. The lack of  $\text{PbO}_2$  formation may be related to the high pH used in the distribution system 9.5-9.9, a range over which the free chlorine is predominantly present as the hypochlorite ion ( $\text{OCl}^-$ ) and not as the more potent oxidant of hypochlorous acid ( $\text{HOCl}$ ). The morphology of the corrosion products was observed by SEM (Figure 3.6), and the products are present as particles in aggregates that have morphologies very different from those of hydrocerussite (hexagonal plates) and cerussite (long bar). Acid digestion showed that the dominant element of the scale was lead (~62%, or 620,000  $\mu\text{g/g}$ ), and trace amounts of manganese (7  $\mu\text{g/g}$ ), iron (9  $\mu\text{g/g}$ ), and vanadium (0.7  $\mu\text{g/g}$ )

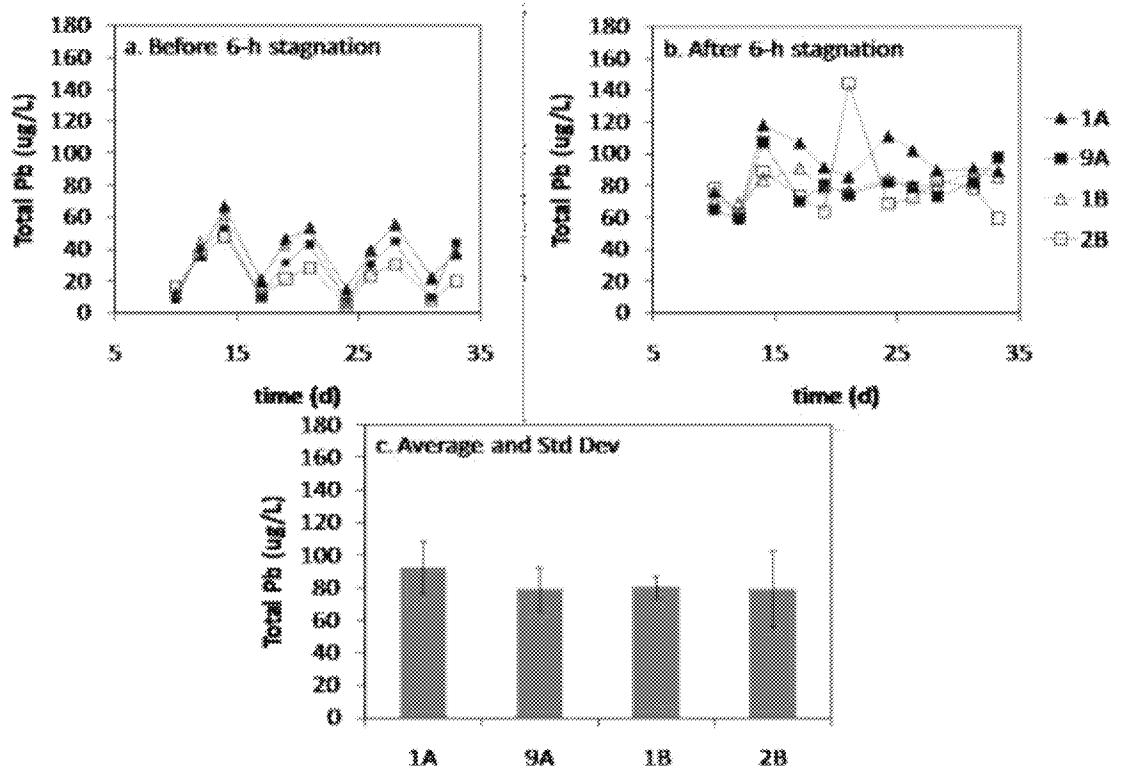
were also observed. The corrosion products may simply scavenge these elements from the water and allow them to accumulate in the pipe scales; vanadium, which is likely present as vanadate, can behave similarly to phosphate and have an affinity for associating with lead (Gerke, Scheckel, and Schock 2009). No calcium, magnesium, or other common cations were detected.

### Conditioning of Providence Pipes

The total lead concentrations during the eight weeks of static conditioning were highest during the first week with an average concentration around 16,000  $\mu\text{g/L}$ . This high value was likely caused by particles that came out of the pipes during sampling; many post-stagnation samples had visible particles. The total lead concentrations decreased during the second week and primarily stayed within the range of 200-2000  $\mu\text{g/L}$ . The variations of total lead concentrations for a given pipe for different sampling times and among different pipes for the same sampling time were still large after eight weeks of static conditioning. The total lead concentration could be dramatically affected by the release of only a few lead-containing particles detaching during the emptying of the pipes following stagnation. The switch from static conditioning to conditioning with recirculating flow was done in part to more readily remove particles most easily detached from the pipe surfaces.

For the static conditioning period the dissolved lead concentrations were much less variable than the total lead concentrations, especially from Weeks 6 to 8, both in terms of pipe-to-pipe variation and day-to-day variation. Except for Pipe 9B, the majority of dissolved lead concentrations were in the range of 60-200  $\mu\text{g/L}$ . Four pipes (1A, 9A, 1B, 2B) from the original eight were selected for further conditioning and then experiments with connections to copper pipes. These four pipes were selected because they had similar average dissolved lead concentrations and their variations in dissolved lead (based on the standard deviation) were the smallest.

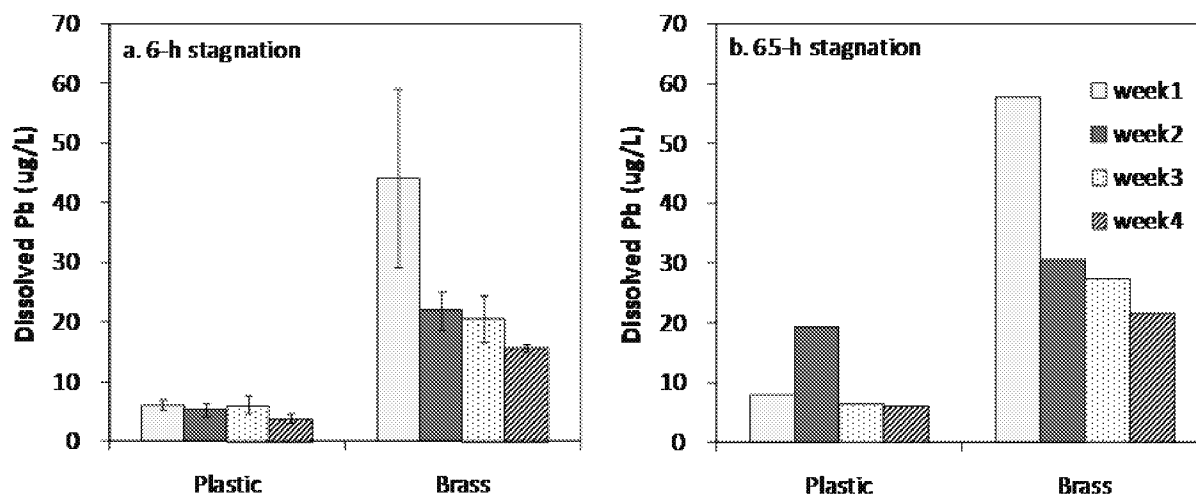
Pipes 1A, 9A, 1B, and 2B were further conditioned in a recirculation mode with intermittent stagnation periods for five weeks before they were connected to copper pipes. The influent concentration increased over the course of each week (Figure 3.7a) because the pipes periodically had recirculating flow modes that caused accumulation of dissolved lead in the reservoir; influent concentrations returned to low values when the influent reservoir was replaced at the beginning of each week. The effluent lead concentrations for the 6-h stagnation periods from Weeks 2 to 5 (Figure 3.7b) were quite stable in the range of 50-100  $\mu\text{g/L}$ , which indicated that the stagnant water in the pipes might be reaching equilibrium with the corrosion products in the pipe scale. The total lead concentration profile was quite similar to the dissolved lead concentration profile, which indicated that only limited particulate lead (defined as the difference between total and dissolved lead) was released during the 6-h stagnation periods. Particulate lead was generally less than 10% of the total lead from Weeks 2 to 5. Relative to the earlier static conditioning phase, the conditioning phase with recirculating flow yielded much more stable total lead concentrations, which suggests that the recirculating flow helped to stabilize the pipe scales and limit the release of particulate lead. The average effluent total lead concentrations for all four pipes were comparable (Figure 3.7c), suggesting that the pipes were well conditioned and ready to be connected to the copper pipes.



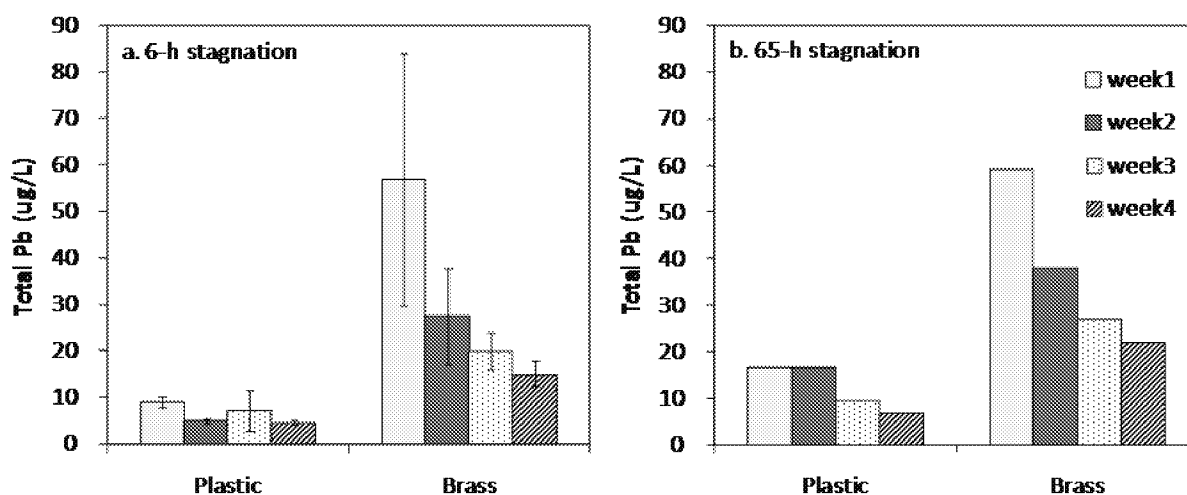
**Figure 3.7 Total lead in recirculating conditioning of pipes from Providence (Weeks 2-5).** Total lead concentration profile during conditioning of the aged lead pipes in the recirculating flow mode from Weeks 2 to 5. Panel “a” shows the influent lead concentration before the 6-h stagnation period; panel “b” shows the effluent lead concentration after 6 hours of stagnation; panel c shows the average effluent lead concentration after the 6-h stagnation periods. Variation bars represent one standard deviation.

### Control Experiments With Couplings and Without Lead Pipes

PVC pipes were connected to copper pipes using plastic and brass couplings to evaluate the lead release from the couplings, reservoir, fittings, and tubing. Dissolved lead concentrations were monitored regularly each week (Figure 3.8). The effluent dissolved lead concentrations were always less than  $7.2 \mu\text{g/L}$  from the plastic coupled PVC-copper pipes. These measurable lead concentrations from an ostensibly lead-free pipe loop indicate the background lead contributed by the reservoirs, tubing, and fittings; however, these concentrations are still very low compared to systems with brass couplings or lead pipe present. The control experiments were performed after the experiments with lead pipes connected to copper pipes. Although efforts were made to clean the reservoirs by acid cleaning and the tubing and fittings by recirculation of a mildly acidic solution, the cleaning may not have completely removed any lead remaining from the earlier experiments. Significant amounts of dissolved lead were released from the brass-coupled copper-PVC pipe assemblies during Week 1 (Figure 3.8a). The lead release might be due to the direct leaching from the brass coupling or to galvanic reactions between the brass coupling and the copper pipe. Lead concentrations in the effluent decreased over time, dropping from  $\sim 40 \mu\text{g/L}$  in Week 1 to  $\sim 20 \mu\text{g/L}$  in Week 4. High lead release in



**Figure 3.8** Dissolved lead in control experiments (no lead pipe) with synthetic Providence water. Effluent dissolved lead concentrations of the control experiment from Weeks 1 to 4 after making connections of copper pipes to PVC pipes after (a) 6-h stagnation periods (average and standard deviation shown) and (b) the 65-h stagnation period.



**Figure 3.9** Total lead in control experiments (no lead pipe) with synthetic Providence water. Effluent total lead concentrations of the control experiment from Weeks 1 to 4 after making connections of copper pipes to PVC pipes after (a) 6-h stagnation periods (average and standard deviation shown) and (b) the 65-h stagnation period.

Week 1 might be due to the disturbance of the system after making the connections and the initial flushing. Therefore, because this research focused specifically on galvanic corrosion phenomena, in the later comparisons of the copper-PVC control experiments with the copper-lead experiments, only the data from Week 2 to Week 4 of the control experiments are emphasized. Increasing the stagnation time from 6 hours to 65 hours only slightly enhanced dissolved lead release, indicating that the system might have reached equilibrium.

The total lead concentration profiles for the control experiments were similar to those of dissolved lead (Figure 3.9). This similarity suggested that very little particulate lead (i.e. the

difference between total and dissolved lead) was released during stagnation. For the brass-coupled system, the total lead concentrations were highest in Week 1, ~60 µg/L after both 6 and 65 hours of stagnation. The concentrations dropped to ~20 µg/L in Week 4. The decreasing trend of the total lead concentration over time suggested that high lead release from the brass-coupled copper and PVC pipes might be a transient effect.

## **Providence Pipes Connected to Copper Tubing**

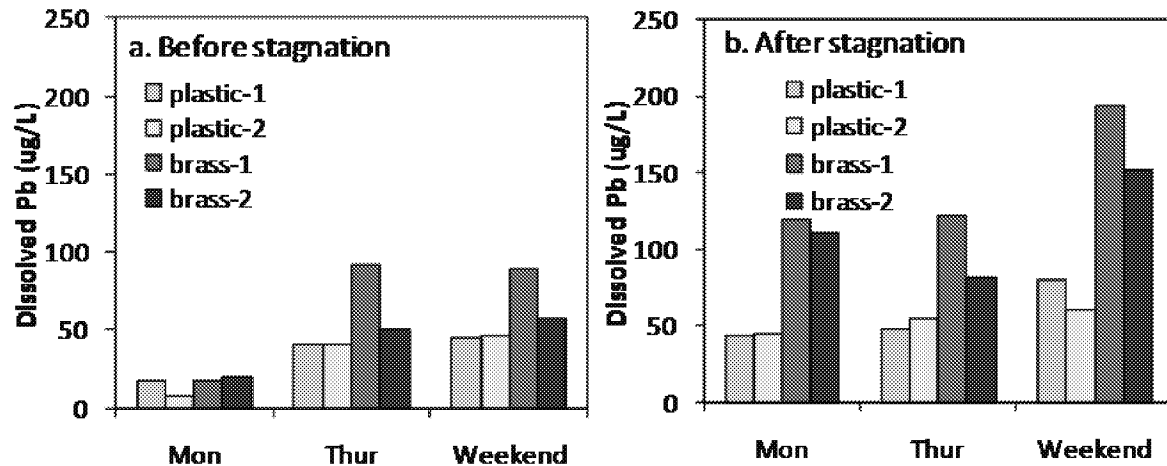
### ***Effect of Coupling Type***

After connecting lead pipes to copper pipes using brass and plastic couplings, dissolved lead concentrations were monitored regularly each week. During the first 2 weeks, when collecting effluent samples, a first 50 ml sample and a second 400 ml sample were collected and measured separately; the reported effluent lead concentration in Figure 3.10 for these weeks is the weighted average of these two values. The concentration profile during each week was similar from Weeks 1 to 6, and Week 2 is used to illustrate the effect of different couplings on lead release. The pH of the reservoir decreased slightly (from 9.8 to 9.3-9.5) from Monday morning to Friday morning. At the same time, the influent dissolved lead concentrations increased with time (Figure 3.10a) due to the accumulation of dissolved lead in the water during the periods of recirculating flow and stagnation. The influent lead concentrations from the pipes with brass fittings increased more during the week than did the concentrations from the pipes with plastic fittings.

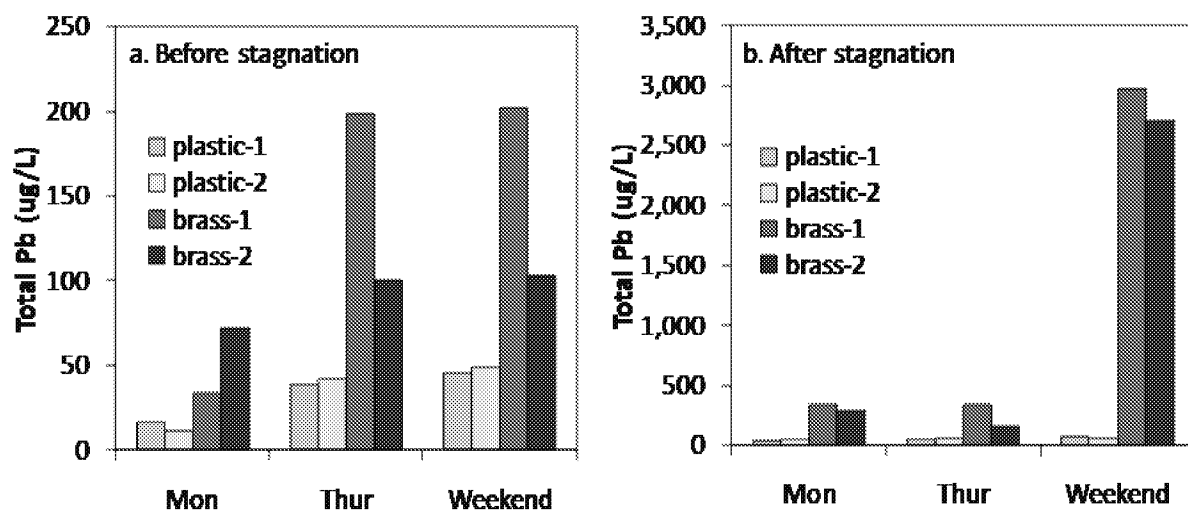
After 6 hours of stagnation, the pH of the water from the pipes with different fittings was not very different and all free chlorine was consumed for all pipes. The effluent dissolved lead concentrations after 6-h stagnation times were significantly higher for pipe assemblies with brass couplings than with plastic couplings. Using plastic couplings, the effluent dissolved lead concentrations were ~50 µg/L following 6 hours of stagnation and they were 50-80 µg/L following the 65-h weekend stagnation period. The duplicate pipe assemblies had comparable values (Figure 3.10b). In contrast to the plastic-coupled pipe assemblies, the pipes with brass couplings had effluent dissolved lead concentrations of ~100 µg/L following the 6-h stagnation period and ~150 µg/L after 65 hours of stagnation. Although the effluent dissolved lead concentration from Pipe 2B (brass-2) was consistently lower than from Pipe 1B (brass-1), the lead release from pipes with brass couplings was still significantly higher than that with plastic couplings. These results suggest that using brass couplings could increase dissolved lead release after partial lead service line replacement.

Total lead concentrations were more variable than the dissolved lead concentrations after connecting the lead and copper pipes, which may be due to an effect of installing the coupling on the mechanical stability of the scales. The total lead concentrations became more stable as the experiment progressed. Therefore results for Week 3 are used to illustrate the effect of different couplings on the release of total lead. The influent lead concentration profile is shown in Figure 3.11a, and overall similar trends to those for dissolved lead were observed (Figure 3.10a). The lead concentrations increased with time, and the concentrations from the pipes with brass couplings were higher than those from pipes with plastic couplings.

The effluent total lead concentrations from the pipes with brass couplings were much higher than those from pipes with plastic couplings (Figure 3.11b). For pipes with brass couplings the total lead concentrations after the 6-h stagnation period were about 200-300 µg/L,



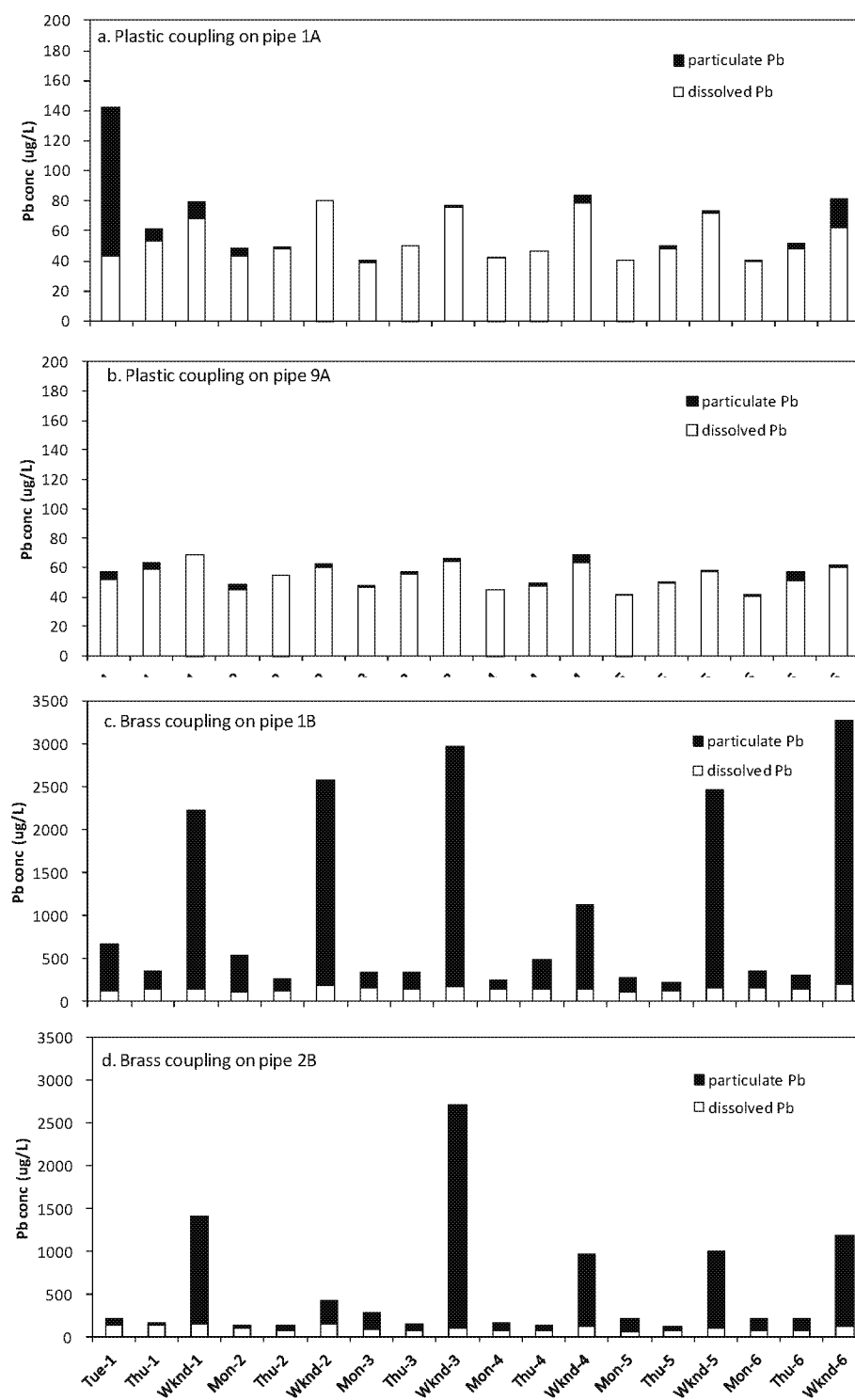
**Figure 3.10** Dissolved lead in coupling experiments (Week 2) with Providence pipes. Dissolved lead concentration in Week 2 of the coupling experiment after making connections of the lead pipes to copper pipes. Panel “a” shows the concentration before stagnation and panel “b” shows the concentration after stagnation.



**Figure 3.11** Total lead in coupling experiments (Week 3) with Providence pipes. Total lead concentration in Week 3 of the experiment with coupled lead and copper pipes. Panel “a” shows the concentration before stagnation and panel “b” shows the concentration after stagnation.

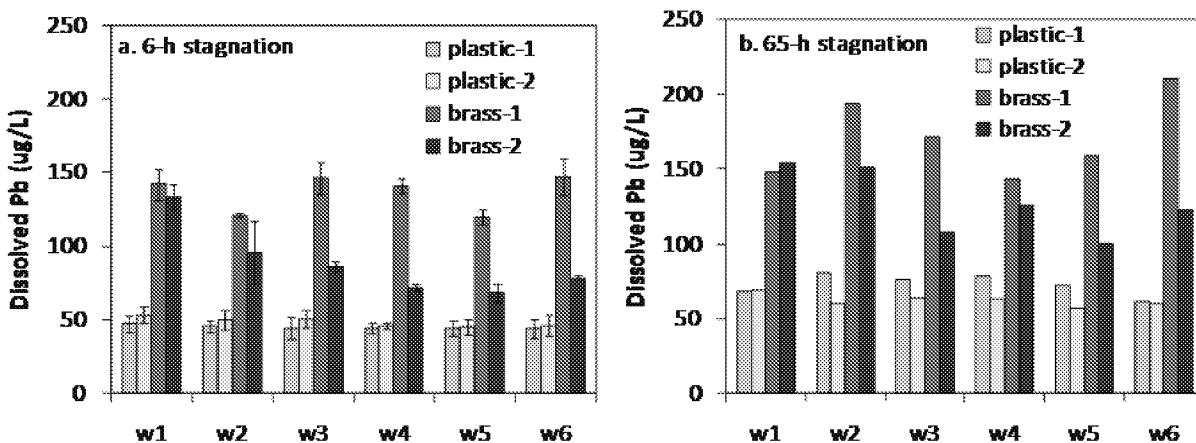
which is more than twice the dissolved lead concentration ( $\sim 100 \mu\text{g/L}$ ). For the longer stagnation time of 65 hours, even more total lead was released with concentrations reaching nearly  $3000 \mu\text{g/L}$ . For this longer stagnation time the total lead concentrations were an order of magnitude higher than the dissolved lead concentrations. For the pipes with plastic couplings, however, the total and dissolved lead concentrations remained quite similar. Results suggest that using brass couplings would have a much greater impact on release of total lead than of dissolved lead.

The distribution of lead between particulate and dissolved forms in the water collected from the pipes after stagnation was evaluated (Figure 3.12). After connecting the lead pipes to



**Figure 3.12** Distribution of lead between dissolved and particulate forms for effluents from Weeks 1 to 6 of experiments with Providence lead pipes connected to copper pipes for (a-b) plastic couplings and (c-d) brass couplings. The axis labels indicate the day of the week (“Wknd” is the 65-h stagnation period) and the week of the experiment.



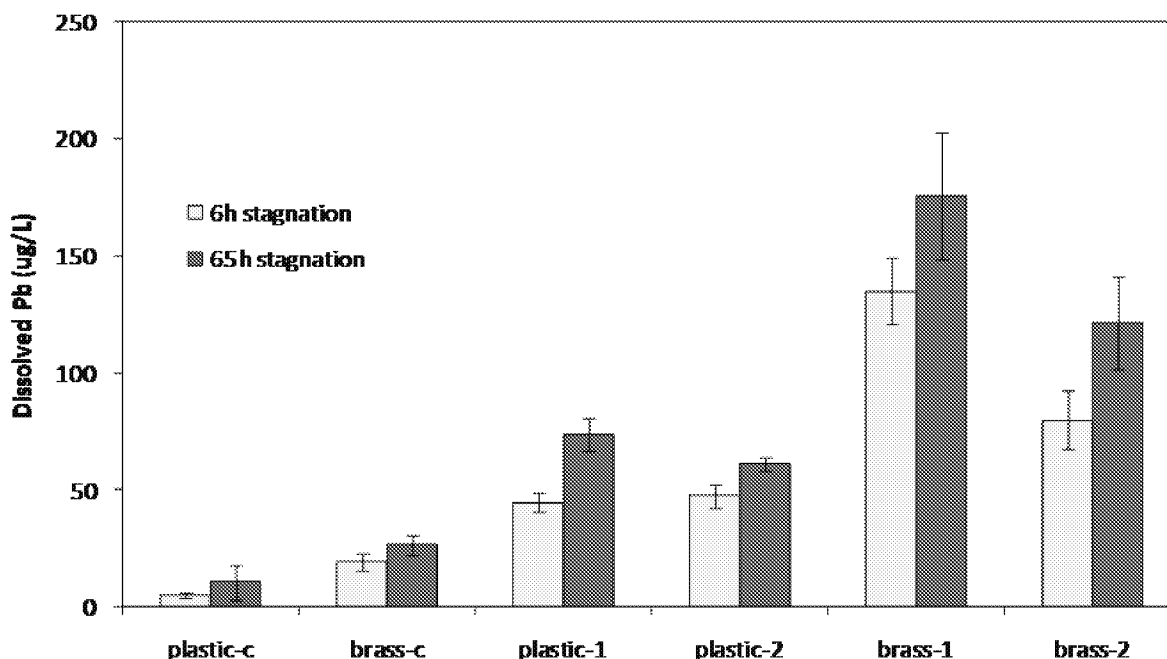


**Figure 3.13. Dissolved lead in coupling experiments with Providence pipes.** Effluent dissolved lead concentrations of the coupling experiment from Weeks 1 to 6 after making connections of the lead pipes to copper pipes. Panel “a” shows the average lead concentration after the 6-h stagnation periods of each week, and variation bars represent one standard deviation; panel “b” shows the lead concentration after the 65-h stagnation period.

the copper pipes with the plastic couplings, some particulate lead was released during the first week. This release might be due to an effect of the coupling method on the mechanical stability of the pipe scales. This effect did not last long, and starting in Week 2 the dissolved lead became dominant (almost more than 90% of the total lead).

### *Effect of Time*

The average dissolved lead concentration in the effluent after the 6-h stagnation periods of each week are shown in Figure 3.13a. Using plastic couplings, the lead concentrations were quite stable around 50 µg/L from Weeks 1 to 6, and the duplicates matched each other very well. These stable results suggest that the water in the pipes may reach equilibrium with the corrosion products during the six hours of stagnation. When using brass couplings, effluent lead concentrations for the duplicate pipe assemblies had slightly different behavior. For Pipe 1B (brass-1), the effluent lead concentrations were not affected by time; while for Pipe 2B (brass-2), effluent lead concentrations decreased from an average of 130 µg/L in Week 1 to 72 µg/L in Week 4 and became stable after Week 4. While both pipes show strong evidence for increased lead release upon connection of the lead pipe to the copper pipe with the brass couplings, the duration of the increased lead release may be affected by variability in the specific properties of pipe scales. General conclusions regarding the duration of the period of galvanic corrosion cannot be made. Despite the decreasing trend for Pipe 2B, the lead concentrations were still higher than for the pipe assemblies that had plastic fittings. For the 65-h weekend stagnation, the trend in effluent dissolved lead concentration from Week 1 to Week 6 was similar to that for the 6-h period (Figure 3.13b).

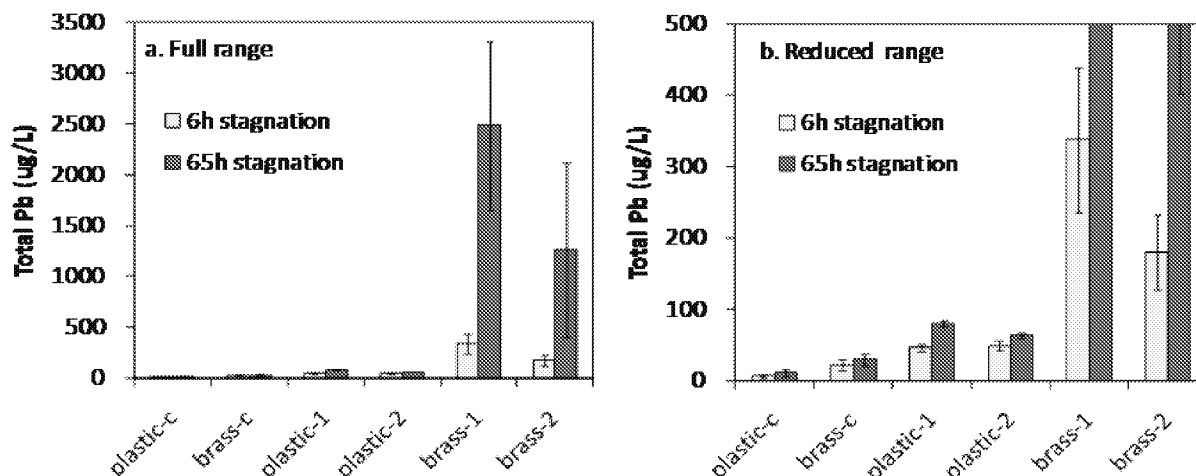


**Figure 3.14. Dissolved lead in coupling experiments (Weeks 2-6) with Providence pipes and control experiments (Weeks 2-4). Average effluent dissolved lead concentration with different stagnation time from Weeks 2 to 6 of the experiment with coupled lead and copper pipes (plastic-1 and -2 and brass-1 and -2) and Weeks 2 to 4 of the control experiment with coupled copper and PVC pipes (plastic-c and brass-c). Variation bars represent one standard deviation.**

### *Effect of Stagnation Time*

After both 6-h and 65-h stagnation periods, dissolved lead release from the pipes using brass couplings was much higher than from pipes with plastic couplings (Figure 3.14). The enhancement of dissolved lead release might be due to either galvanic corrosion or to leaching of lead from the brass fitting. The control experiments with only the brass fitting observed release of 20-30  $\mu\text{g/L}$  of dissolved lead, which is higher than the difference between the dissolved lead concentrations during the condition of the lead pipes and those measured with connected lead and copper pipes; consequently, the increase in dissolved lead release upon connection of the pipes with the brass fitting can be attributed to both galvanic corrosion and direct release from the fitting. For both coupling types, slightly more dissolved lead was released over the weekend stagnation periods than over the 6-h stagnation periods, suggesting that stagnation time was an important parameter in lead release. The difference in dissolved lead between the 6-h and the 65-h stagnation times was measurable but small, which suggests that the water may be approaching but not quite reaching equilibrium with the corrosion products. The similarity of the trend after both 6-h and 65-h stagnation periods suggested that the probable impact of galvanic corrosion was not obscured by stagnation time.

Stagnation time is an important factor in total lead release. Figure 3.15 shows the average total lead concentrations from Week 2 to Week 6 after 6-h and 65-h stagnation periods. After both stagnation periods, significantly more lead was released from the brass-coupled systems than from the plastic-coupled systems. After six hours of stagnation, about 200 – 300



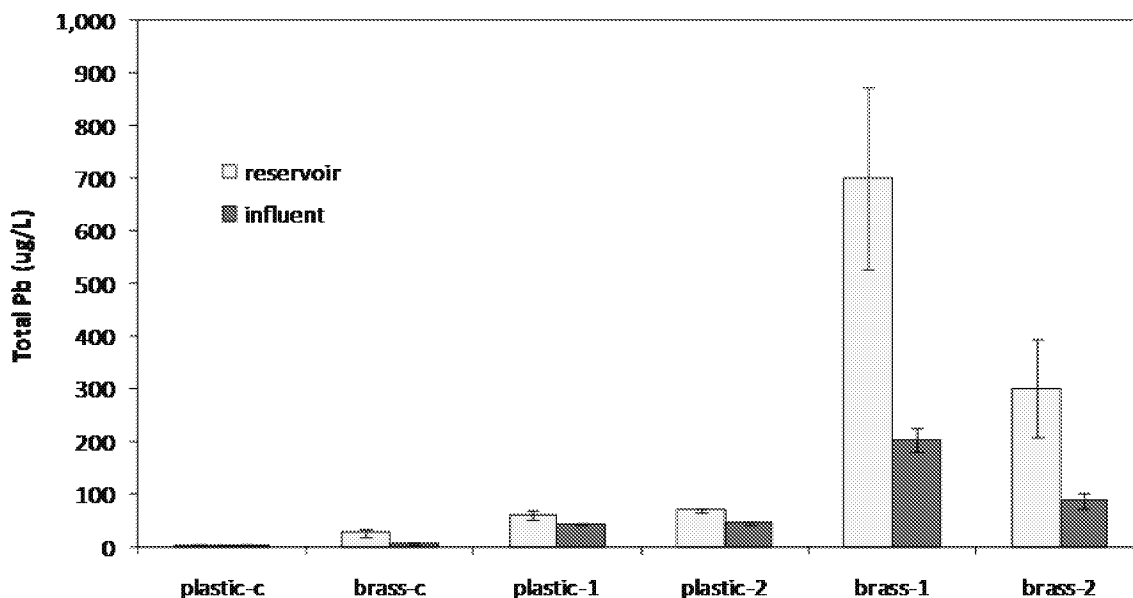
**Figure 3.15.** Total lead in coupling experiments (Weeks 2-6) with Providence pipes and control experiments (Weeks 2-4). Average effluent total lead concentration with different stagnation time from Weeks 2 to 6 of the experiment with coupled lead and copper pipes (plastic-1 and -2 and brass-1 and -2) and Weeks 2 to 4 of the control experiment with coupled copper and PVC pipes (plastic-c and brass-c). Panel “a” shows the y-axis with the full range of concentrations measured, while panel “b” shows the y-axis range to 500 µg/L. Variation bars represent one standard deviation.

µg/L total lead was released from the pipes using brass fittings, while only about 80 µg/L total lead was released from the plastic-coupled pipes. Although brass may be a potential source for lead release, it only provided ~20 µg/L total lead based on the control experiments. Therefore, the greater amount of total lead released from the brass-coupled systems can be attributed to the galvanic reaction between the lead and copper pipes.

Increasing the stagnation time significantly increased the total lead release from the brass-coupled systems but not from the plastic-coupled systems. After the 65-h stagnation period, more than 1000 µg/L lead was released, which was several times higher than following the 6-h stagnation period. Given the fact that only a limited amount of lead (30 µg/L) was released from the brass fittings after 65-h stagnation in the lead pipe-free control experiments, the greater amount of lead release over the longer stagnation time is due to the galvanic reaction of the lead and copper pipes. Comparison of the high total lead and limited dissolved lead release suggested that the impacts of galvanic corrosion are greater for total lead release than for dissolved lead release.

Particulate lead was especially dominant after the weekend stagnation when it comprised more than 90% of the total lead. The high level of particulate lead in the pipes with brass couplings may be due to two reasons. The first reason was that the accelerated release of lead due to the galvanic connection may have created local dissolved lead concentrations that were high enough to exceed the saturation of some lead(II) minerals (e.g., hydrocerussite), thus causing the precipitation of secondary solids and increasing particulate lead. A second reason may be that the galvanic action destabilized the scales of the pipes and caused portions of the scales to break off and be released to the water as particulate.

The pH changes were also different for the different stagnation times. After six hours of stagnation, the pH in the effluent did not change much (dropped about 0.1 units) in any of the pipes. However, after 65 hours of stagnation, the pH dropped 0.2-0.3 pH units in the pipes using



**Figure 3.16 Lead in acidified reservoirs in coupling experiments (Weeks 2-6) with Providence pipes and control experiments (Weeks 2-4). Average total lead concentration in the reservoir before (“influent”) and after (“reservoir”) acidification from Week 2 to Week 6 of the experiments with lead pipes connected to copper pipes (plastic-1 and -2 and brass-1 and -2), and from Weeks 2 to 4 of the control experiment with coupled copper and PVC pipes (plastic-c and brass-c). “Influent” indicates the samples collected from the reservoir before the weekend stagnation, and “reservoir” denotes the samples collected in the acidified reservoir after the reservoir was replaced the following Monday. Variation bars represent one standard deviation.**

plastic couplings and the pH in the pipes using brass couplings actually increased 0.2-0.3 pH units. The reasons for the different changes in pH are not currently known. For galvanic corrosion the reaction on the lead anode ( $\text{Pb}(0) = \text{Pb}^{2+} + 2\text{e}^-$ ) generates  $\text{Pb}^{2+}$ , which is a Lewis acid that can slightly lower the pH, but in the same system the reaction on the copper cathode ( $0.5\text{O}_2 + 2\text{e}^- + \text{H}_2\text{O} = 2\text{OH}^-$ ) generates  $\text{OH}^-$  and can increase the system pH. The balance of these processes as well as formation of corrosion products may be the cause of the different changes in pH for the differently coupled systems.

### ***Total Lead Mobilized During Recirculation***

During the recirculation periods and following stagnation periods for which samples were not collected, particulate lead could accumulate in the reservoirs. Measuring the total lead concentration in the reservoir can therefore help estimate this accumulation of lead-containing particles. Each week after replacing the old reservoir with a clean one with freshly prepared solution, the water remaining in the old reservoir was acidified and samples were collected after 24 hours. Figure 3.16 shows the average total lead concentrations in the acidified reservoir from Week 2 to 6 along with the total lead concentration in the solution that was the influent to the last stagnation period of the week. This last influent includes the total lead that was sufficiently mobile to be recirculated, and a comparison of its concentration with that in the acidified

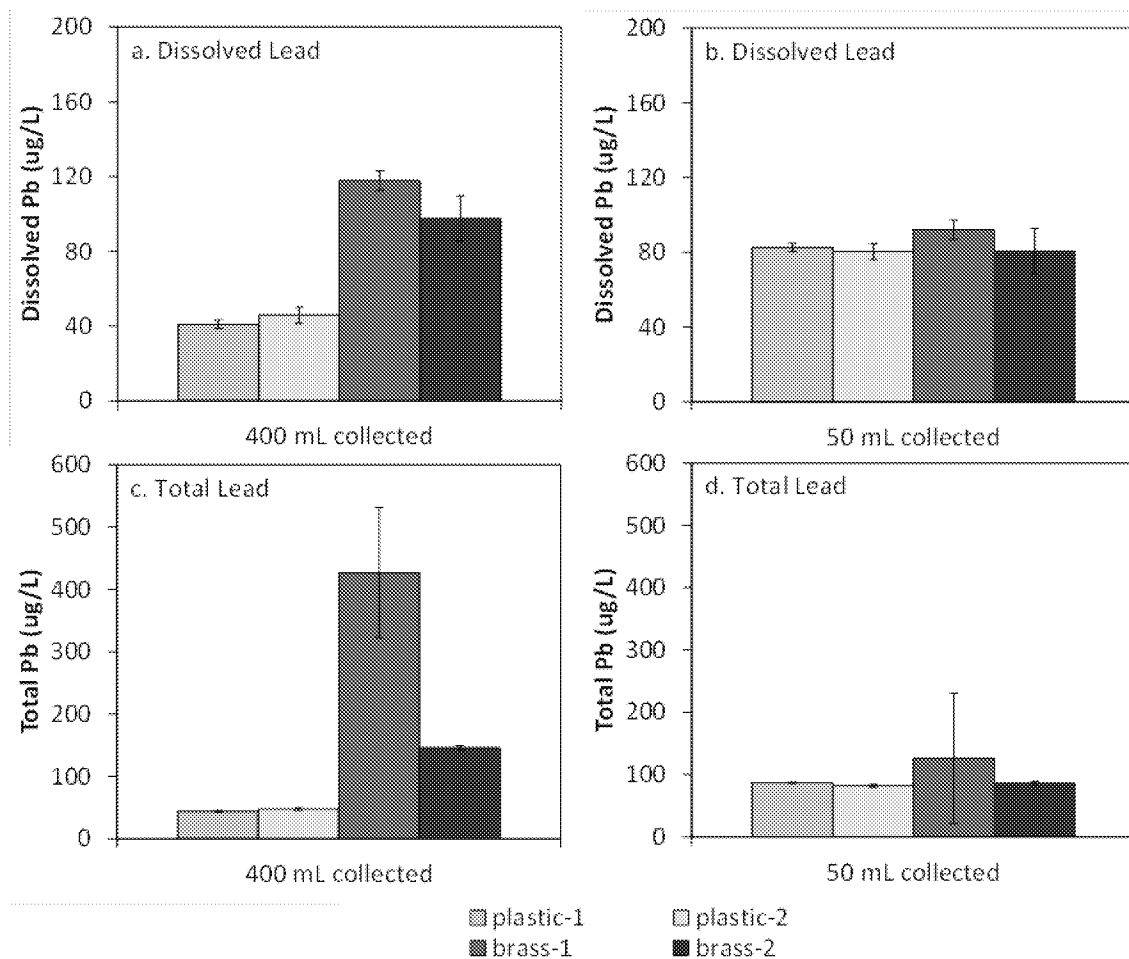
reservoir yields information on the total lead that had accumulated in the reservoir. For the pipes using plastic couplings, the total lead concentrations in the acidified reservoir were a little bit higher than those prior to acidification, indicating that some particulate lead accumulated. However, for the pipes using brass couplings, the total lead concentrations in the acidified reservoir were three times higher than those prior to acidification, which suggests that significant amounts of particulate lead had been released during the recirculation periods and had accumulated in the reservoir.

The particulate lead that accumulated in the reservoir can be attributed to the lead release from the recirculation periods and the stagnation periods that were not sampled. Therefore, the total lead release over one week can be estimated as the sum of the lead in all samples that were collected and the lead in the acidified reservoir. Using this approach, the total weekly lead release from the lead pipes with plastic couplings was sufficient to yield 50 to 70  $\mu\text{g/L}$  for the 10 L water used in the recirculation loop. Based on the lead pipe-free control experiments, the brass fittings and other unexpected lead sources could yield an additional 30  $\mu\text{g/L}$ . Therefore, up to 100  $\mu\text{g/L}$  lead would be released from the lead pipes with brass fittings if there was no effect of galvanic corrosion. However, the pipe assemblies with brass couplings yielded total concentrations of 300 to 1000  $\mu\text{g/L}$  per week. These results confirmed that galvanic corrosion can significantly increase the release of lead, especially particulate lead, for at least the six weeks of study.

### ***Localization of Lead Release***

In Week 2 of the experiment, the effluent after the 6-h stagnation period was collected in two separate samples, a 50-mL sample followed by a 400-mL sample. Since the volume of each lead pipe was about 120 mL and the copper pipes had volumes of 310 mL, the dissolved lead concentration of the 50-mL sample represented the lead release far from the coupling, and the lead release near the coupling could be measured in the 400-mL sample. For the 50-mL samples, the dissolved lead concentrations were very similar (in the range of 80 to 90  $\mu\text{g/L}$ ) for pipes with both types of couplings. In contrast, the 400-mL samples had much higher dissolved lead concentrations for the pipes with brass couplings than for the pipes with plastic couplings (Figure 3.17a). A similar trend was observed for the total lead (Figure 3.17b). For the 50-mL samples, the total lead concentrations were comparable for all the pipes, although the concentration from pipe 1B (brass-1) was a bit higher than from the other pipes, which might be attributed to the easily mobilization of the lead particulates. For the 400-mL samples, however, the total lead concentrations for the brass-coupled systems were significantly higher than those for the plastic-coupled systems. More lead was released from pipe 1B (brass-1) than pipe 2B (brass-2), which might be due to variability in the specific properties of pipe scales.

The greater amount of lead released near the brass coupling could be due to either galvanic corrosion or the direct release from the brass coupling. Based on the control experiments,  $\sim 20$   $\mu\text{g/L}$  dissolved lead and  $\sim 30$   $\mu\text{g/L}$  total lead could be released from the brass fittings after six hours of stagnation, which was much lower than the difference between the lead concentrations from the brass-coupled system and the plastic-coupled system. The difference between the two systems was especially large for total lead. These results suggest that the greater lead release near the coupling can be partially attributed to the galvanic corrosion of the lead and copper pipes. Further, the galvanic corrosion is localized to the portion of the pipe closest to the coupling. The lead concentrations in this local region may be much higher than those in the overall 400-mL sample since the 400-mL sample also includes water that had been

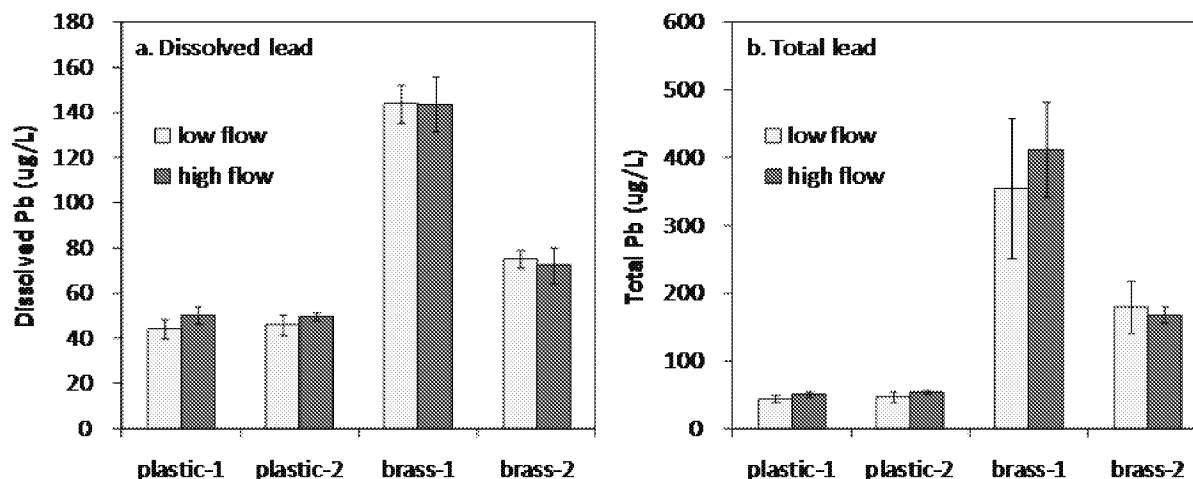


**Figure 3.17** Dissolved (a and b) and total (c and d) lead concentrations for sampling methods that collected 400 mL of water (a and c) or 50 mL of water (b and d) from the pipe assemblies with Providence pipes. A 400 mL sample included all of the water in the lead pipe as well as some from the copper tubing, and a 50 mL sample collected water only from one end of the lead pipe. Variation bars represent one standard deviation. Note that different concentration ranges are used for a-b and c-d.

stagnant in the copper pipe that would not have released any lead. Indeed, for the plastic couplings the effect of diluting the water from the lead pipe section with water from the copper pipe section is apparent in the higher dissolved lead concentrations for the 50-mL sample than for the 400-mL sample. In contrast, even with the dilution of the water from the copper pipe section, the dissolved lead concentration for the pipes with brass couplings was higher for the 400-mL sample than for the 50-mL sample.

### *Effect of Sampling Velocity*

Effluent samples on Wednesdays in Weeks 4 and 6 after the 6-h stagnation period were collected at a higher flow rate of 3.6 L/min, and the average concentrations were compared with the effluent samples collected at a lower flow rate of 1 L/min in these same two weeks (Figure 3.18). At a flow rate of 3.6 L/min (0.95 gal/min), the Reynolds Number was 4750 and

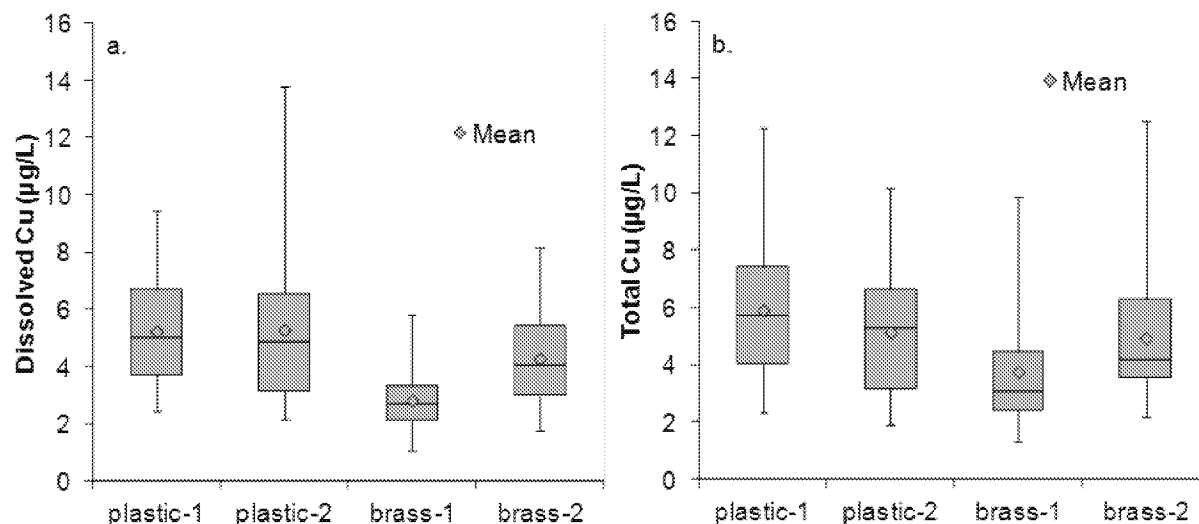


**Figure 3.18** Lead concentration with different sampling flow rates for Providence pipe experiments. Average (a) dissolved and (b) total lead concentration after 6 hours of stagnation with samples collected at different flow rates (low flow = 1 L/min and high flow = 3.6 L/min) from Week 4 and 6. Variation bars represent one standard deviation.

the flow is expected to be turbulent flow, and at 1 L/min (0.26 gal/min) the Reynolds Number was 1320 and laminar flow is expected. Despite the different flow rates and expected flow regimes, there was little difference in total or dissolved lead concentrations for these two flow rates. At both flow rates, the total and dissolved lead release from the pipes using brass couplings was much higher than from pipe assemblies with plastic couplings. This result indicates that for the range of velocities studied, there is no effect of sampling velocity on the lead concentrations in the system. However, for higher flow rates than those examined in these experiments, increasing flow rate may result in higher lead concentrations in the samples. A recent study of lead-copper pipe assemblies performed by a different group, found significant spikes of particulate occurring at higher flow rates of 8 and 32 L/min (2.11 and 8.26 gal/min) as compared to their low flow rate of 1.3 L/min (0.34 gal/min) (Cartier et al. 2011). The diameters of the pipes in that study were similar to those in the present study, so the relationship between flow rate and velocity and associated laminar versus turbulent flow would be similar.

### *Release of Copper*

Dissolved and total copper concentrations were also monitored after different stagnation times. Both the dissolved and total copper concentrations were low in the effluent (Figure 3.19), well below the LCR Action Level for copper of 1300 µg/L. The dissolved and total copper concentrations were similar for each sample, so most copper was dissolved. The copper concentration was higher in the first week, which might be due to the initial flush of the new copper pipes after making the connections. Copper concentrations were similar for the pipe assemblies with plastic couplings and brass couplings, indicating that copper release was not affected by the galvanic corrosion. Very little copper release was expected since copper would be acting as the cathode in galvanic corrosion, and in a galvanic couple the cathode is actually protected from corrosion by its connection to the anode.



**Figure 3.19** Copper in coupling experiments with Providence pipes. Box-and-whisker plots of the (a) dissolved and (b) total copper concentrations in the effluent after 6-h and 65-h stagnation over Weeks 1 to 6 of the experiments with connected lead and copper pipes. Dots represent the mean, boxes represent the 25th and 75th percentiles, the line in the box represents median, and whisker bars represent min-max values.

### Effect of Orthophosphate Addition on Lead Release

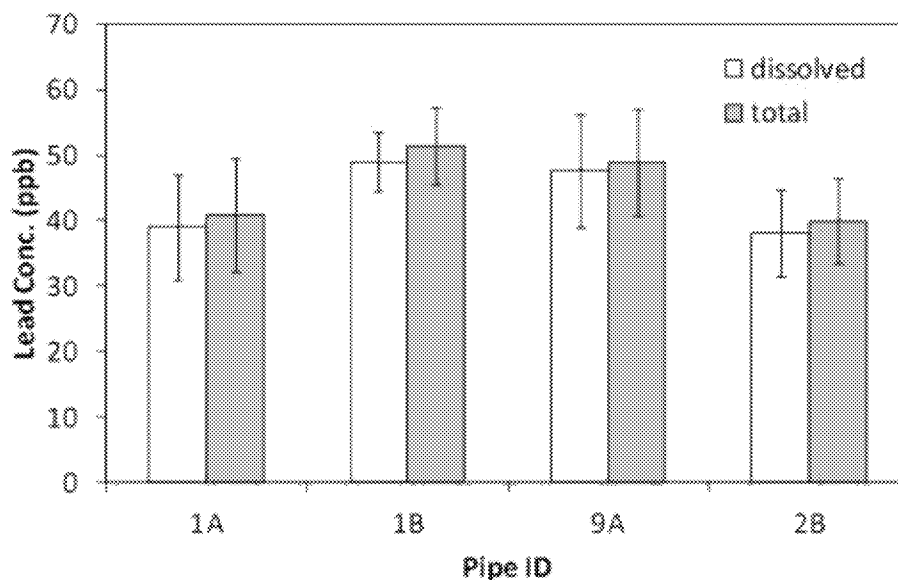
#### *Re-Conditioning after Storage of Pipes*

The four pipes were conditioned in the static mode for seven weeks and both the total and dissolved lead concentrations were quite stable over time. The average dissolved lead concentrations were quite similar for the four pipes within the range of 60 – 85 µg/L. The total lead concentrations were higher than the dissolved lead concentrations, between 75 µg/L and 105 µg/L. The total lead concentrations for Pipe 2B were a little bit lower than for the other three pipes. The four pipes were further conditioned in the recirculating flow mode for three weeks to remove particles that could be easily detached from the pipe surfaces. Both the total and dissolved lead concentrations were lower after being conditioned in the recirculation flow mode than they were during conditioning in the static mode (Figure 3.20). The average dissolved lead concentrations following 6-h stagnation periods were 40 to 50 µg/L. The total lead concentrations were quite similar to the dissolved lead concentrations, suggesting that only limited amounts of particulate lead were released during conditioning.

#### *Lead and Copper Release Following Connection to Copper Tubing*

After connecting lead pipes to copper tubing using low-lead brass couplings, dissolved and total lead concentrations were monitored regularly each week. Addition of orthophosphate inhibited lead release from the low-lead brass-coupled pipe assemblies. Compared to that without orthophosphate, addition of 2.5 mg/L as PO<sub>4</sub> orthophosphate decreased the average dissolved and total lead concentrations by more than 50% following six hours of stagnation. For all the pipe assemblies, both the dissolved and total lead concentrations after 6-h stagnation



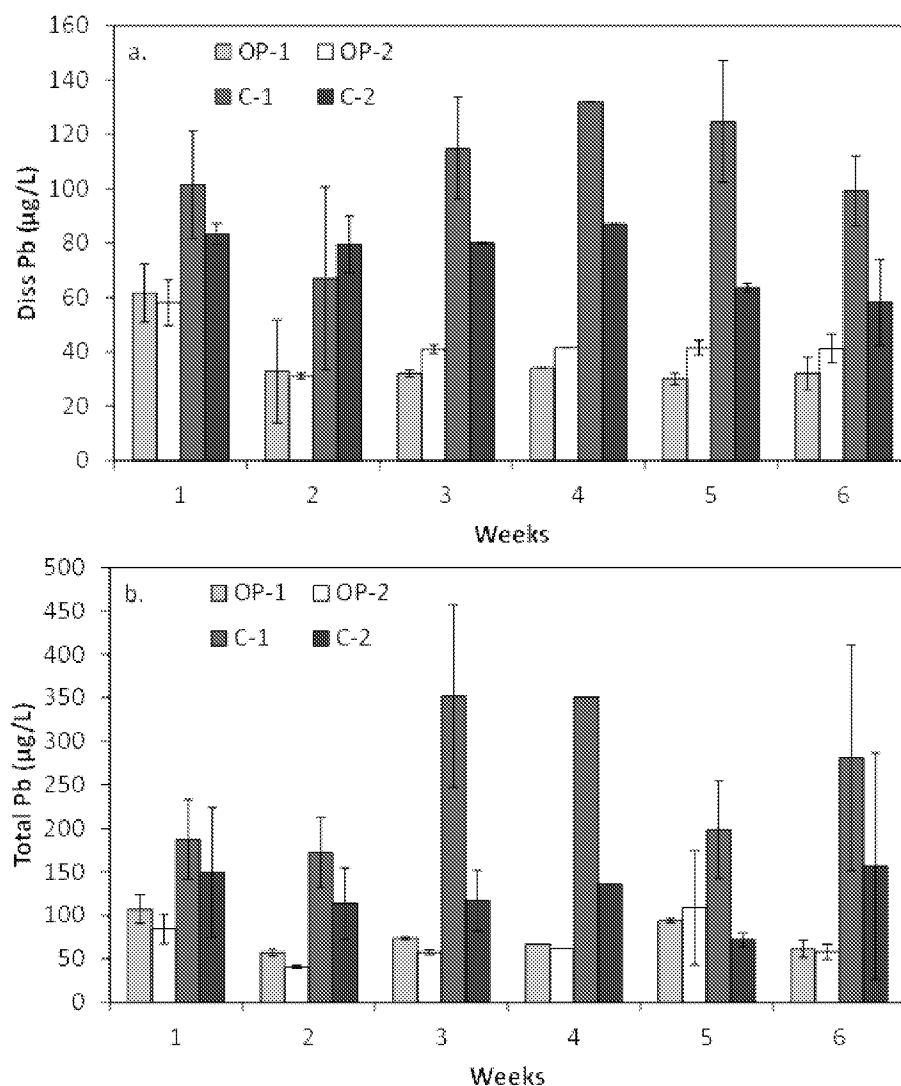


**Figure 3.20 Lead in recirculating conditioning of Providence pipes in preparation for experiments with orthophosphate. Average dissolved and total lead concentrations in the effluent after 6-h and 65-h stagnation in the recirculating-flow conditioning mode. Variation bars represent one standard deviation.**

periods were stable over the six weeks of the experiments (Figure 3.21). The total lead concentrations were higher than the dissolved lead concentrations, indicating the release of some particulate lead.

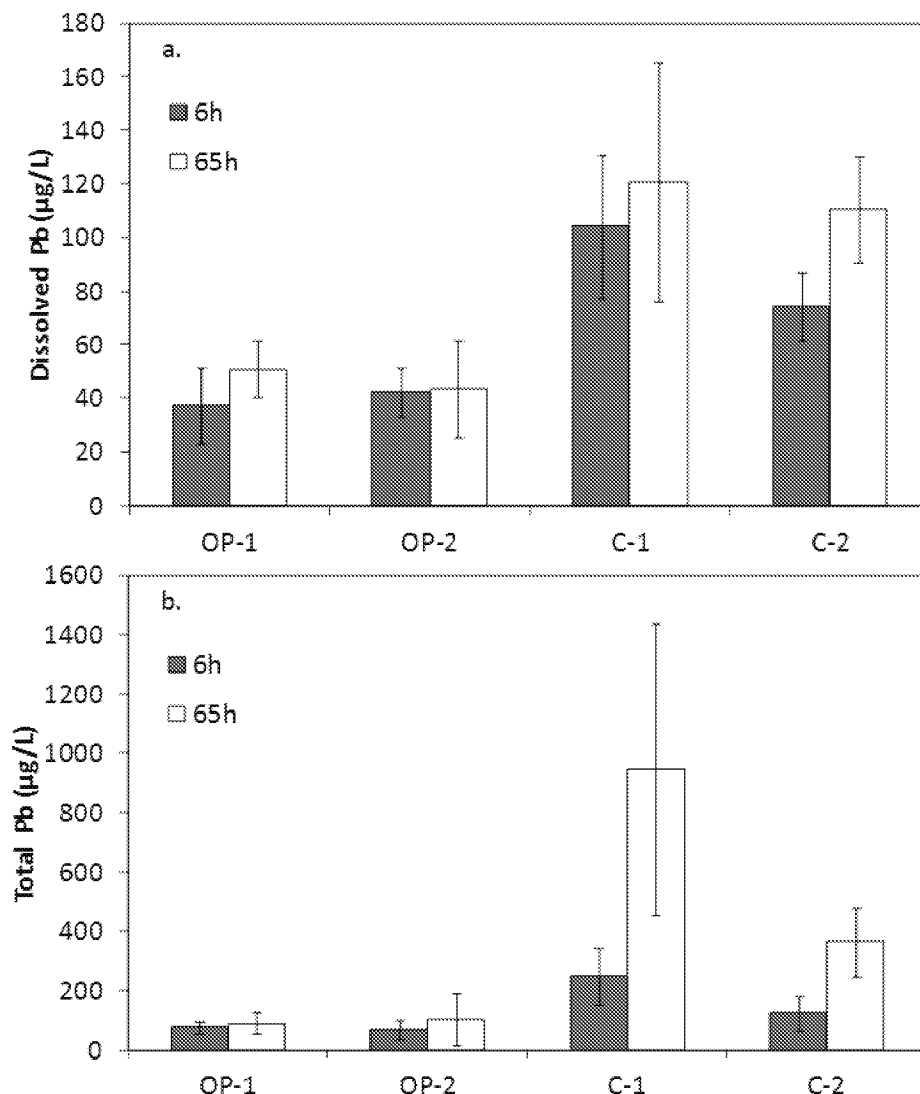
The lead concentrations in C-1 (no orthophosphate added) were similar to those in the brass-coupled systems from the earlier experiments performed in 2011. The lead concentrations in pipe assemblies OP-1 and OP-2 were more similar to those in the plastic-coupled systems from 2011, and lead concentrations in C-2 were in between those from the plastic- and brass-coupled pipe assemblies from 2011. These results indicate that the presence of orthophosphate certainly did not increase lead concentrations and that orthophosphate may be able to mitigate lead release due to galvanic corrosion. Orthophosphate may limit lead release even at the high pH of the Providence Water, which is consistent with equilibrium solubility predictions. Orthophosphate is often recommended for use at pH values closer to neutral where the reductions in solubility can be about two orders of magnitude, but the calculated decrease in solubility is still about an order of magnitude at pH 9-10.

Increasing the stagnation time from six hours to 65 hours slightly increased the dissolved lead concentrations for all the pipe assemblies (Figure 3.22a). For the systems without orthophosphate, the dissolved lead concentrations were close to the predicted equilibrium solubility of plumbonacrite (Figure 3.23), which observations that plumbonacrite was the dominant corrosion product in the pipe scales. For the systems with orthophosphate, the dissolved lead concentrations were above the equilibrium solubility of the lead(II) phosphate hydroxypyromorphite, and were still closer to the equilibrium solubility of plumbonacrite. The formation of a lead(II) phosphate scale that could control lead concentrations at lower values may take longer than six weeks. The formation would probably also be faster if higher doses of orthophosphate were used.



**Figure 3.21 Lead concentrations over time for Providence pipes with and without added orthophosphate. Dissolved (a) and total (b) lead concentrations after 6-hour stagnation periods with lead pipes connected to copper tubing using low-lead brass couplings. Variation bars represent one standard deviation.**

Increasing the stagnation time from six hours to 65 hours significantly increased the total lead concentrations for the pipe assemblies without orthophosphate, and it only slightly enhanced the total lead concentrations for the systems with orthophosphate (Figure 3.22b). The distribution of total lead between particulate and dissolved was determined for all the pipe assemblies (Figure 3.24). For assemblies OP-1 and OP-2, dissolved lead was generally more abundant than particulate lead, except for a few points where particulate lead was more dominant. For assembly C-1, particulate lead was more dominant than dissolved lead. For C-2, dissolved lead was more abundant after 6-h stagnation periods; while particulate lead became dominant after 65 hours of stagnation. Addition of orthophosphate may be mitigating lead release from galvanic corrosion by limiting the release of particulate lead.

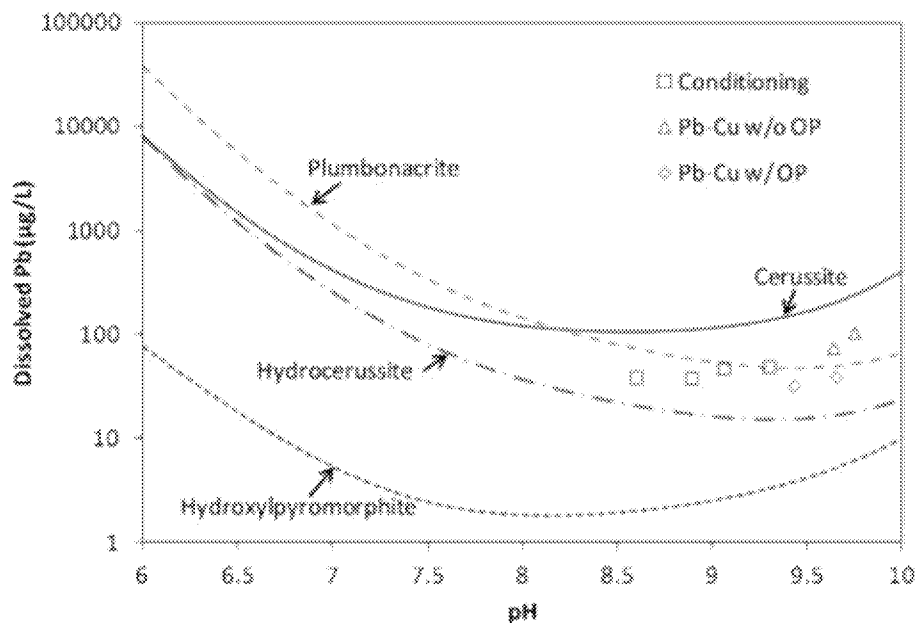


**Figure 3.22 Lead concentrations with Providence lead pipes connected to copper tubing. Average post-stagnation (a) dissolved and (b) total lead concentrations are shown for both 6-hour and 65-hour stagnation times. Variation bars represent one standard deviation.**

Copper concentrations were monitored regularly each week for all four pipe assemblies. Most copper was dissolved and not particulate in all of the experiments. The copper concentrations were similar for systems with and without orthophosphate, and increasing the stagnation time from six hours to 65 hours increased the copper concentrations for all the pipe assemblies (Figure 3.25). The addition of orthophosphate may mitigate lead release from galvanic corrosion, but it only has a very limited impact on copper release.

### Conclusions From Experiments with Providence Pipes

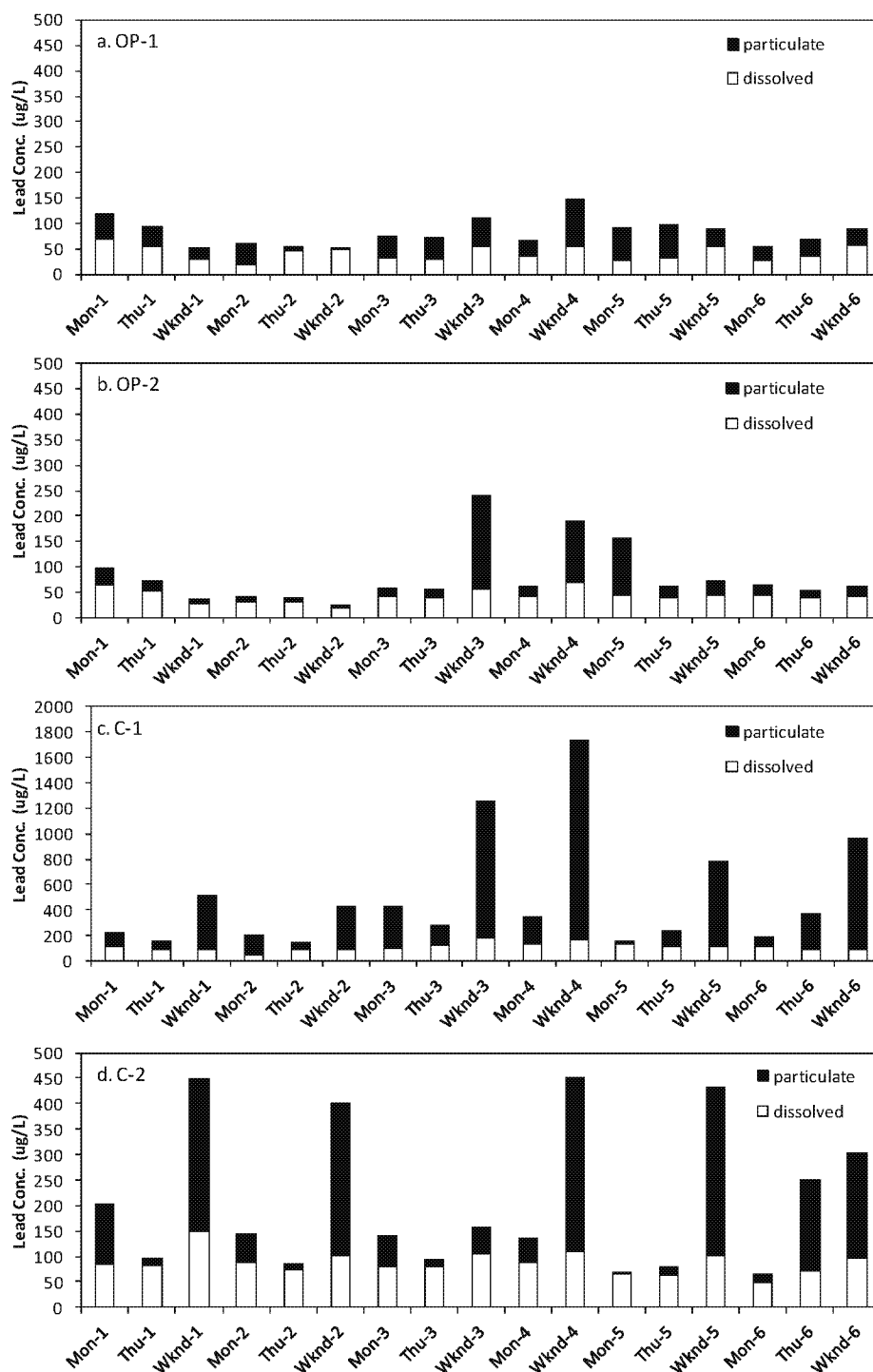
The effect of galvanic corrosion on lead release was investigated using aged lead pipes from Providence. Before conducting the experiments, the pipes were conditioned using a static “dump-and-fill” procedure and a recirculating flow mode for a total of 13 weeks. This length of



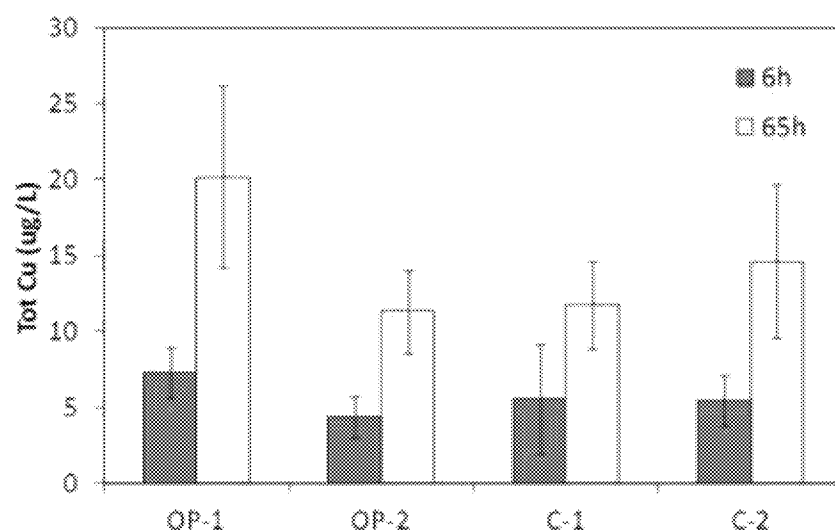
**Figure 3.23 Predicted equilibrium solubility. Average dissolved lead concentrations in the conditioning in the recirculation flow mode and in the experiments with Providence lead pipes connected to copper tubing (points) and predicted lead concentrations in equilibrium with different corrosion products (lines).**

conditioning was sufficient for a set of four pipes to have similar behavior. Experiments were then conducted in a recirculation flow mode with intermittent stagnation periods using two different kinds of couplings, brass and plastic, to connect the conditioned lead pipes to new copper pipes. Release of dissolved and particulate lead was higher for systems with brass couplings than for systems with plastic couplings, which was due to the galvanic corrosion and the direct release from the brass coupling. Control experiments with brass and plastic couplings that connected PVC instead of lead pipes to copper pipes were able to isolate the lead release that could be attributed to release from the couplings. Based on the limited lead release from the brass couplings in the present control experiments, galvanic corrosion was the primary source that contributed to the significant lead, especially total lead, release from the brass-coupled systems. For the brass-coupled systems, longer stagnation times (65 hour versus 6 hour) resulted in dramatically more release of particulate lead and only slightly greater release of dissolved lead. Sampling of different volumes following stagnation showed that lead release for the systems with brass couplings was greater for the region closest to the coupling. For the six weeks of the experiment, galvanic corrosion persisted and was not a transient effect.

The effect of orthophosphate on lead release following simulated PLSLRs was investigated using aged lead pipes harvested from Providence, RI. Addition of orthophosphate effectively inhibited lead release in the low-lead brass-coupled pipe assemblies. These results suggest that orthophosphate certainly did not enhance lead release from galvanic corrosion. Instead, the presence of orthophosphate may mitigate lead release due to galvanic corrosion for a system with water chemistry similar to that of Providence.



**Figure 3.24** Distribution of lead between dissolved and particulate forms following stagnation periods during Weeks 1 to 6 of experiments with Providence lead pipes connected to copper tubing using low-lead brass couplings. The labels on the x-axis indicate the day of the week and the week of the experiment. Weekend (Wknd) samples had 65 hours of stagnation and all other samples were after six hours of stagnation.

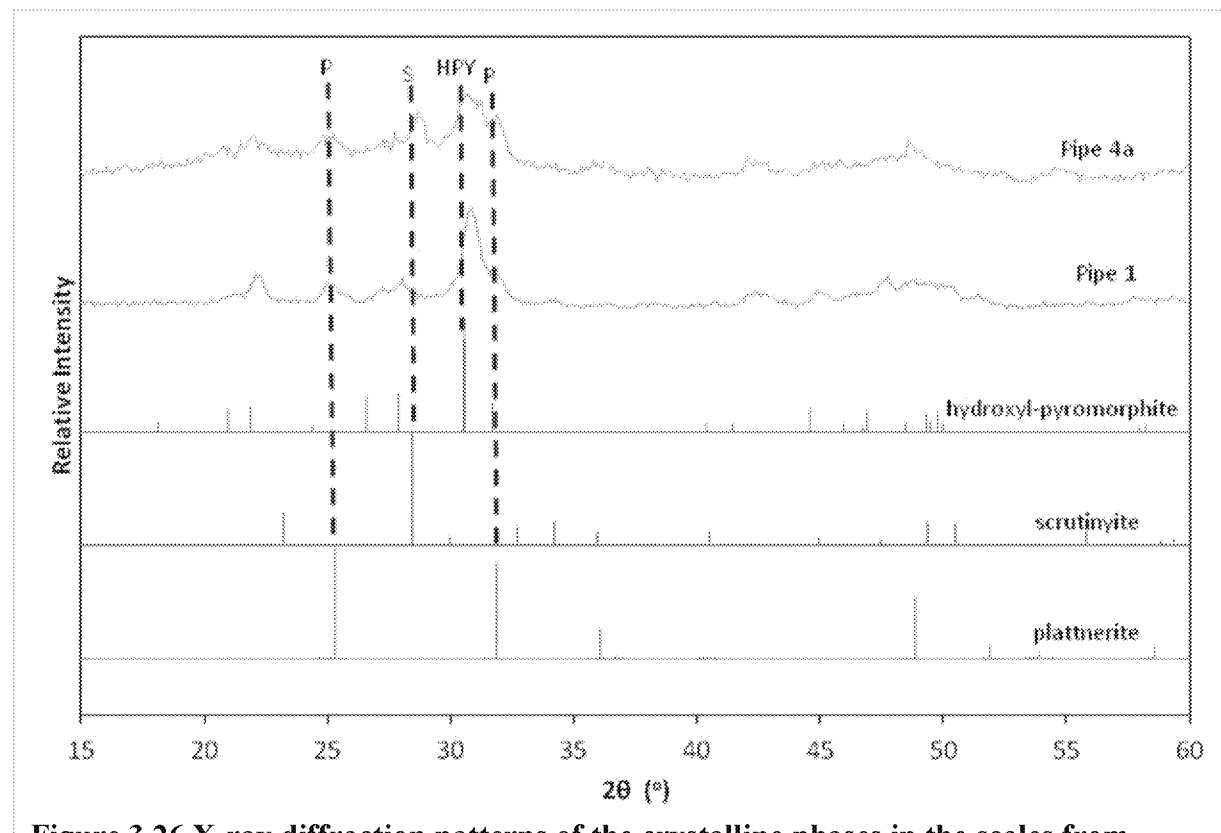


**Figure 3.25** Copper in the experiments with Providence lead pipes connected to copper tubing. Average post-stagnation total copper concentrations are shown for both 6-hour and 65-hour stagnation times. Variation bars represent one standard deviation.

## EXPERIMENTS WITH PIPES FROM WASHINGTON, DC

### Characterization of the Pipes

Pipe scales from two pipes (Pipes 1 and 4a) were used for characterization. These scales were taken from the sections of the pipe that were left over after cutting the 24-inch sections needed for the experiments. XRD patterns (Figure 3.26) showed that the dominant crystalline phase in the scales of both pipes was the lead(II) phosphate hydroxylpyromorphite ( $\text{Pb}_5(\text{PO}_4)_3\text{OH}$ ). Scrutinyite ( $\alpha\text{-PbO}_2$ ) was also observed in one of the pipe scales, and plattnerite ( $\beta\text{-PbO}_2$ ) was observed in both of the pipe scales. No other solid phases were indicated by XRD. The formation of the corrosion products may be related to the water chemistry in the DC drinking water distribution system. Prior to 2000 the system used free chlorine as the disinfectant with concentrations as high as 3 mg/L as  $\text{Cl}_2$ , which provided a high oxidation reduction potential (ORP) that has been shown in both lab-scale experiments and field observations to promote the formation of  $\text{PbO}_2$ . During 2000 the residual disinfectant was switched from free chlorine to chloramines, which lowered the ORP and destabilized  $\text{PbO}_2$ . In recent years to control lead release, orthophosphate has been added, and its presence can mitigate



**Figure 3.26** X-ray diffraction patterns of the crystalline phases in the scales from Washington, DC, pipes. Powder diffraction file patterns for hydroxylpyromorphite (04-012-9459), scrutinyite (04-008-7674), plattnerite (01-071-4820), cerussite (01-085-1088) and hydrocerussite (01-073-4362) from the International Centre for Diffraction Data are shown for reference. Dominant peaks associated with hydroxylpyromorphite (HPY), scrutinyite (S), and plattnerite (P) are indicated.

lead release by forming the low-solubility solid lead(II) phosphate hydroxylpyromorphite. The observation of this solid as the dominant corrosion product in the harvested lead pipes is in accordance with the thermodynamic predictions of the solid that should be present in equilibrium with water at the given pH, alkalinity, and orthophosphate concentration. The presence of hydroxylpyromorphite together with the  $\text{PbO}_2$  solids indicates that a transformation from lead(IV) in  $\text{PbO}_2$  to lead(II) phosphate in the scales has been occurring since the introduction of orthophosphate to the water in the distribution system.

Completely digesting the scales determined that trace amounts of aluminum (15 mg/g), manganese (5 mg/g), vanadium (4 mg/g), and copper (6 mg/g) were present. Manganese and vanadium were also observed in the scales of the lead pipes from Providence. Gerke et al. (2009) analyzed the scales of 15 lead pipes from eight different distribution systems and found that most scales contained vanadium with a concentration of 2 to 8 mg/g scale. They proposed that vanadium may be present as vanadinite ( $\text{Pb}_5(\text{VO}_4)_3\text{Cl}$ ). Due to the similar structure of  $\text{VO}_4^{3-}$  and  $\text{PO}_4^{3-}$ ,  $\text{VO}_4^{3-}$  may even substitute for  $\text{PO}_4^{3-}$  in the lead phosphate solids in the pipe scales.

### Conditioning of Pipes

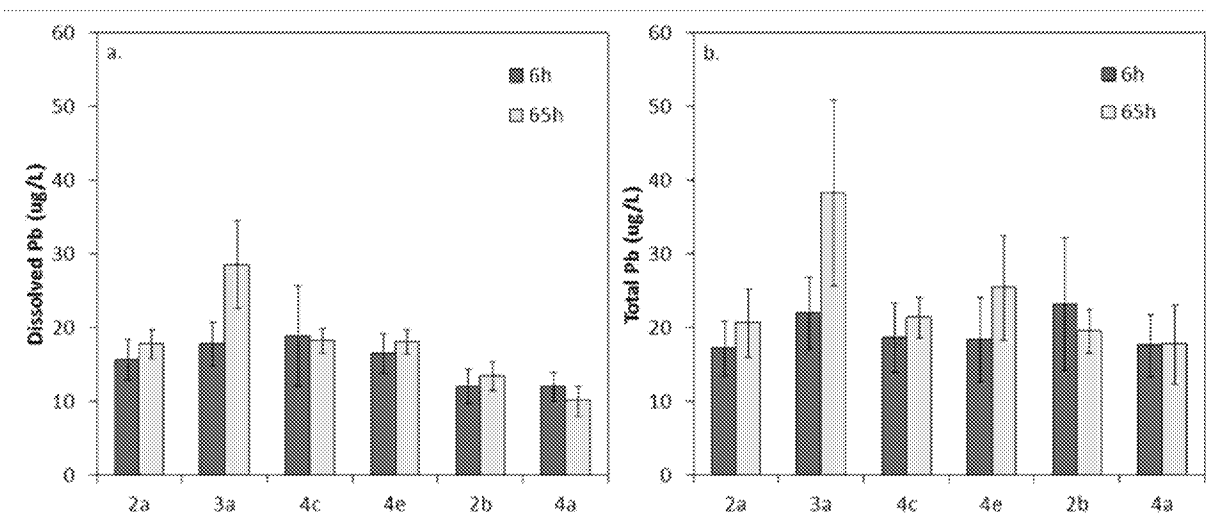
The pipes were first conditioned in a static dump-and-fill mode and then in the system with recirculating flow and intermittent stagnation periods. Pipes 2a, 3a, 4c, and 4e were conditioned for eight weeks and Pipes 1, 2b, 4a, and 4b were conditioned for a total of 23 weeks in the static mode. The average total lead concentrations after Week 6 were similar for all eight pipes, with the average value around 30  $\mu\text{g/L}$ . Pipes 2a, 2b, 3a, 4a, 4c, and 4e were then conditioned in the recirculating flow mode with intermittent stagnation periods for four weeks before being connected to copper tubing. The average dissolved lead concentrations following 6-h stagnation periods were quite similar for the six pipes (Figure 3.27a). Increasing the stagnation time to 65 hours did not affect the dissolved lead concentrations except for Pipe 3a, suggesting that the water in the pipes may have reach equilibrium with respect to the corrosion products within six hours. The total lead concentrations were slightly higher than the dissolved lead concentrations and similar for the six pipes (Figure 3.27b), indicating only limited particulate lead release in the flow from the pipe after the prescribed stagnation periods.

The two pipes selected for use in experiments with low-lead brass (Pipes 1 and 4b), which were added to the scope of work after the first six pipes had been investigated, were conditioned in the static mode for more than 30 weeks and then to three weeks in the recirculating flow mode. For these two pipes in the recirculating flow mode. The dissolved lead concentrations were around 8  $\mu\text{g/L}$  after 6-h stagnation periods and 10  $\mu\text{g/L}$  after 65-h stagnation periods, and the total lead concentrations were higher, around 12  $\mu\text{g/L}$  (Figure 3.28).

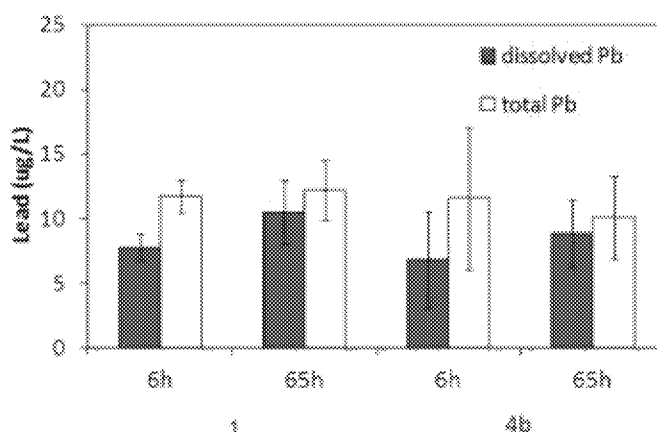
### Control Experiments With Couplings and Without Lead Pipes

PVC pipes were connected to copper tubing using plastic and three types of brass couplings (standard brass, low-lead brass, and brass-dielectric) as control experiments to evaluate the lead release from the couplings, reservoir, fittings, and tubing. Dissolved lead concentrations were monitored regularly each week. For the plastic-coupled PVC-copper pipe assemblies, the effluent lead concentrations after either 6-h or 65-h stagnation were less than 5  $\mu\text{g/L}$  (Figure 3.29a), indicating the background lead contributed by the reservoirs, tubing, and fittings; however, these concentrations are still very low compared to systems with brass





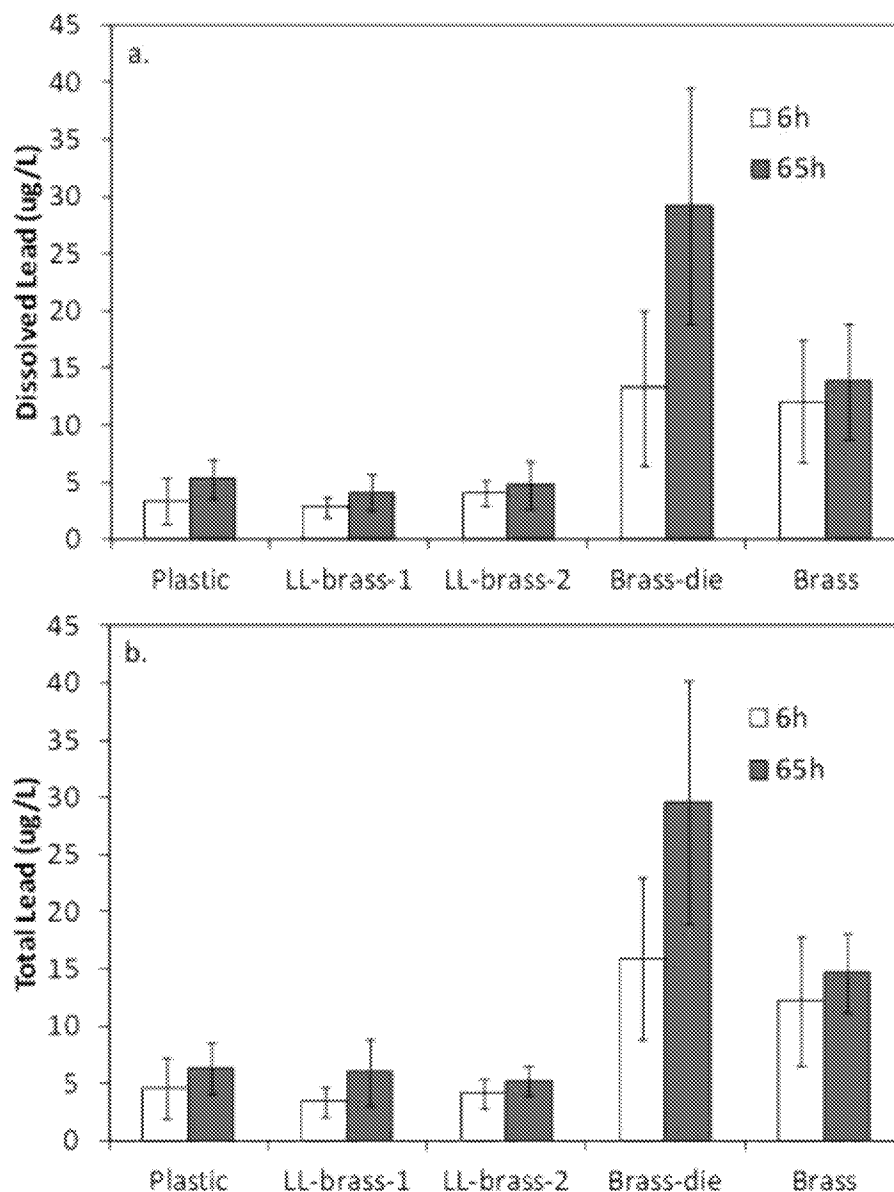
**Figure 3.27** Lead in recirculating conditioning of Washington, DC, pipes. Average dissolved (a) and total (b) lead concentrations in the effluent after 6-h and 65-h stagnation in the recirculating-flow conditioning mode. Variation bars represent one standard deviation.



**Figure 3.28** Lead in recirculating conditioning of Washington, DC, pipes in advance of low-lead brass experiments. Average dissolved and total lead concentrations in the effluent after 6-h and 65-h stagnation in the recirculating-flow conditioning mode. Variation bars represent one standard deviation.

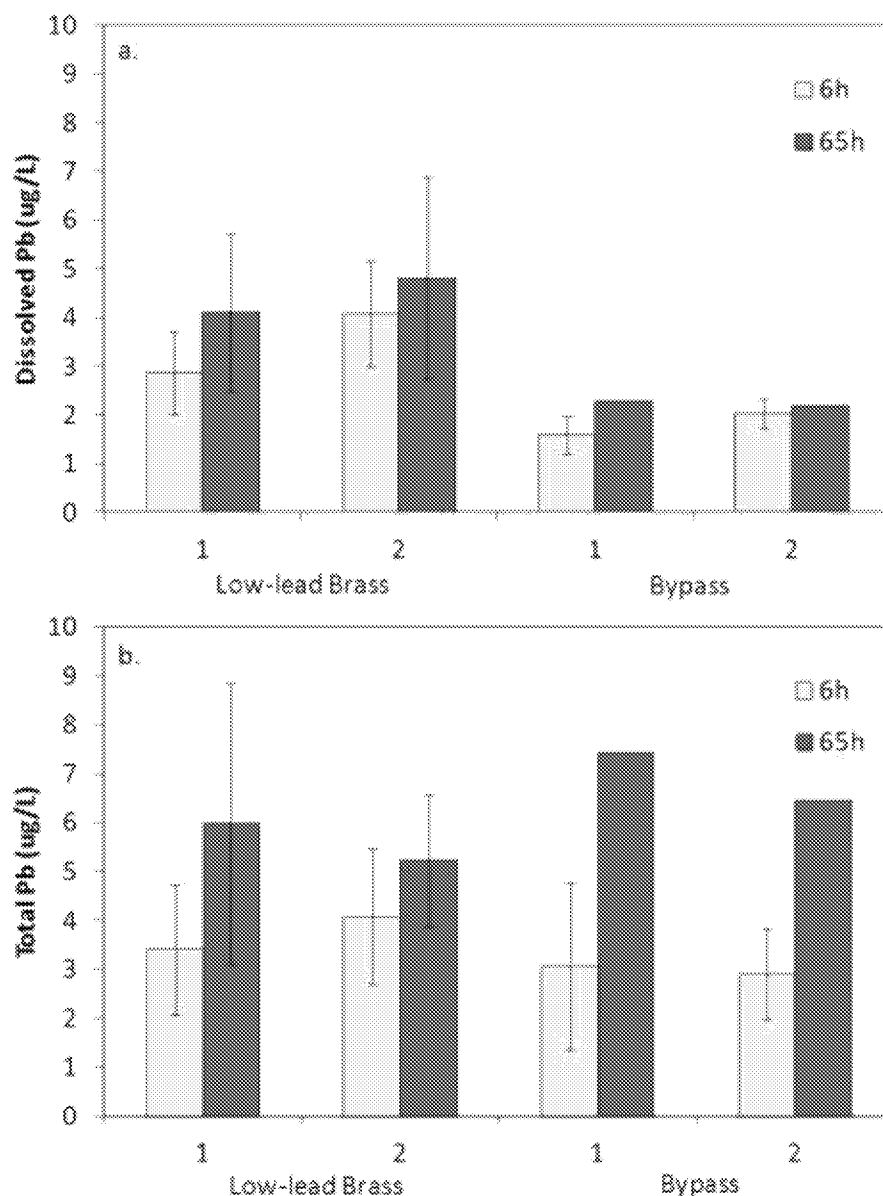
couplings or lead pipe present. On average, around  $15 \mu\text{g/L}$  dissolved lead was released after 6-h stagnation, and increasing the stagnation time to 65-h slightly enhanced lead release. With the low-lead brass couplings, less than  $5 \mu\text{g/L}$  dissolved lead was released after either 6-h or 65-h stagnation, which was significantly less than the concentrations reached when using the conventional brass or brass-dielectric couplings. The total lead concentration profiles for the control experiments were similar to those of dissolved lead (Figure 3.29b). This similarity suggested that very little particulate lead (i.e. the difference between total and dissolved lead) was released from the brass couplings.

Ideally the brass coupling would be the only source of lead; however, approximately  $5 \mu\text{g/L}$  lead concentration in the plastic-coupled copper-PVC systems suggested that sources other than the couplings may be present and contribute to the lead release. To distinguish lead



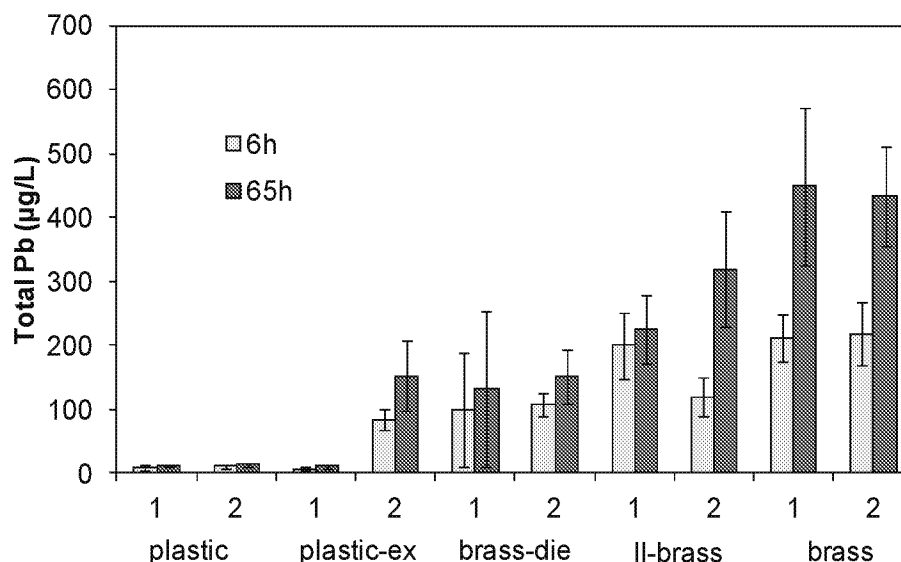
**Figure 3.29. Lead in control experiments (no lead pipe) with synthetic Washington, DC, water. Average dissolved (a) and total (b) lead concentrations in the effluent after 6-h and 65-h stagnation after connecting PVC or CPVC pipes to copper tubing using different couplings. LL-brass denotes the low-lead brass coupling, and Brass-die is a dielectric coupling made with conventional brass. Variation bars represent one standard deviation.**

release from the low-lead brass from other sources, the low-lead brass-coupled copper-CPVC pipe assemblies were bypassed for one week. In the bypassed systems the water was still circulated through the reservoir, tubing, and three-way sampling valves. Both the dissolved and total lead concentrations for this bypassed system were lower than without bypassing the brass couplings, except for the total lead after 65 hours of stagnation (Figure 3.30). Although lead release from the low-lead brass-coupled system was generally higher than from the bypassed system, the difference was not very large. By comparing the lead concentrations in the bypassed



**Figure 3.30** Lead in control experiments (no lead pipes) with synthetic Washington, DC, water. Average dissolved (a) and total (b) lead concentrations in the effluent after 6-h and 65-h stagnation after connecting CPVC pipes to copper tubing using low-lead brass couplings. ‘Bypass’ denotes that the pipe assemblies were bypassed. Variation bars represent one standard deviation.

and un-bypassed systems, the low-lead brass coupling may at most release 1  $\mu\text{g/L}$  total lead after 6 or 65 hours of stagnation periods. The three-way sampling valves were the most likely source of the lead in the bypassed systems, and these sampling values would also have been a source for the systems without the bypass. Some lead-containing particles may have accumulated in the three-way sampling valves.



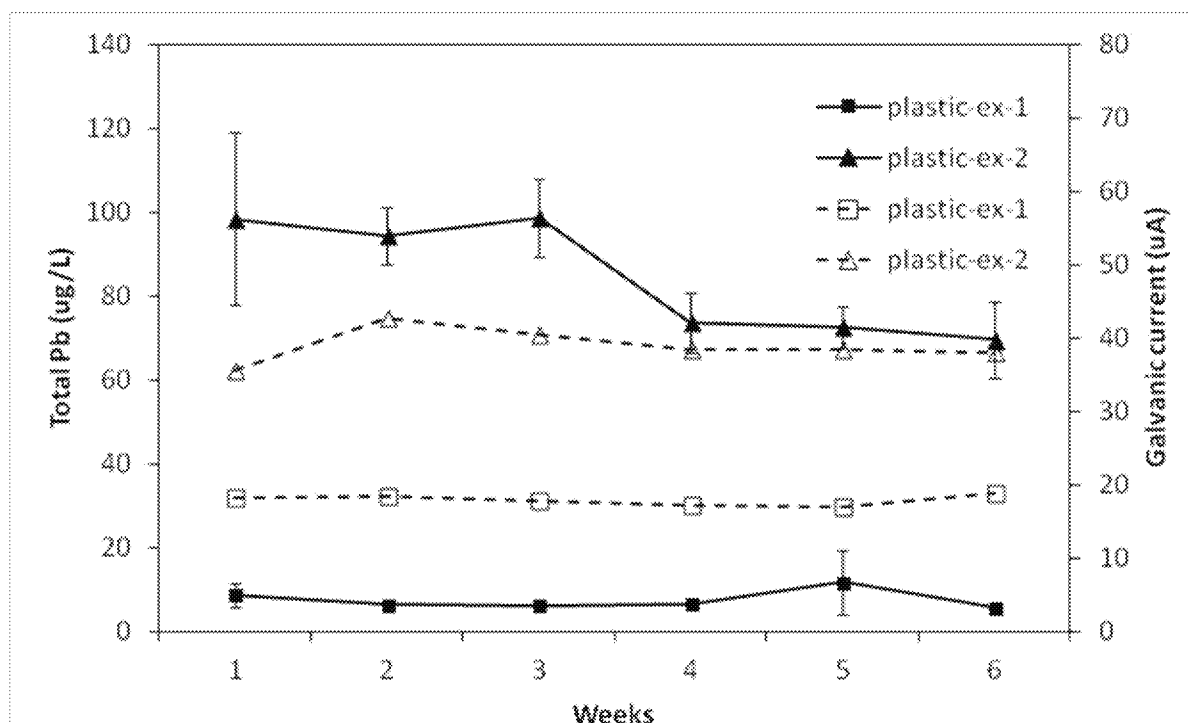
**Figure 3.31 Lead in experiments with Washington, DC, lead pipes connected to copper tubing. Average post-stagnation total lead concentrations are shown for both 6-hour and 65-hour stagnation times. Variation bars represent one standard deviation.**

### Washington, DC, Pipes Connected to Copper Tubing

#### *Effect of Coupling Types*

After connecting lead pipes to copper tubing using the different types of test couplings, dissolved and total lead concentrations were monitored regularly each week. Generally, the effluent lead concentrations after stagnation were lowest for the plastic-coupled systems, which is in accordance with the assumption that there is no galvanic connection in the plastic-coupled pipe assemblies. Relative to the plastic-coupled systems, the total lead concentrations increased in the order of systems coupled with plastic with external wires, brass dielectric fittings, low-lead brass, and conventional brass fittings after the 6-h stagnation period (Figure 3.31). For the brass dielectric-coupled pipe assemblies, galvanic reactions would occur between lead and brass but not between lead and copper, while for the brass- or low-lead brass-coupled pipe assemblies, galvanic reactions between lead and copper and between lead and brass could occur simultaneously. So it is not surprising that lead release from the systems using brass couplings (standard or low-lead) was higher than that from the brass dielectric-coupled systems. The fact that less lead was released from the low-lead brass-coupled systems than from the conventional brass-coupled systems does indicate that there are benefits of using the low-lead brass couplings even though impacts of galvanic corrosion can still occur. Increasing the stagnation time to 65 hours significantly increased lead release from the systems connected with either conventional or low-lead brass couplings, and the increase in time slightly enhanced lead release from the systems using the externally wired plastic and brass dielectric connections.

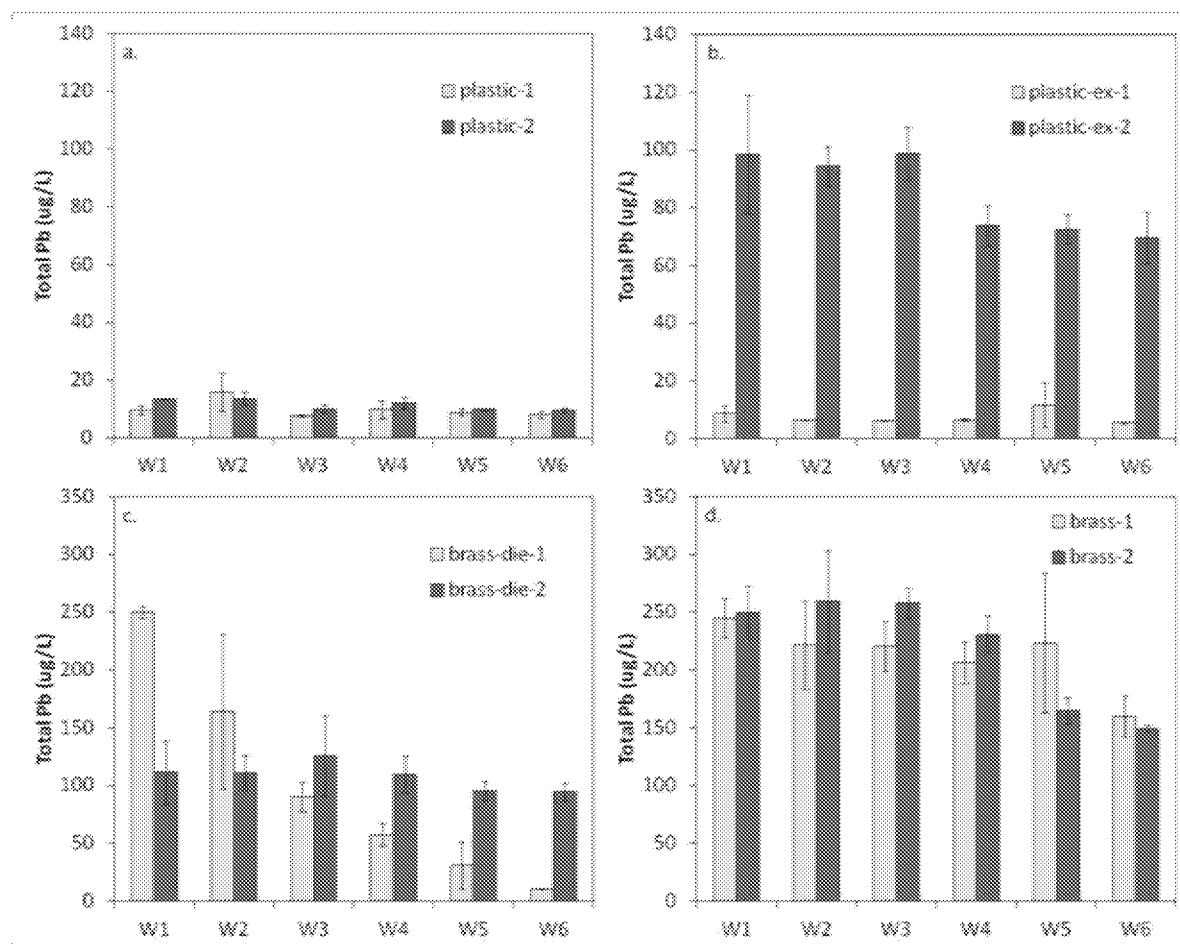
The enhancement of lead release for the externally wired connections can be attributed to galvanic corrosion. Connecting the lead and copper with external wires in the plastic-coupled systems allowed galvanic corrosion of the lead to occur through its connection to the copper tubing. Galvanic current was detected in both of the external galvanic wired plastic-coupled



**Figure 3.32** Total lead concentration and galvanic current after 6 hours of stagnation from experiments with Washington, DC, lead pipes connected to copper tubing using plastic couplings with external galvanic wires. Solid lines and closed symbols represent total lead concentration, and dashed lines and open symbols indicate galvanic current. Variation bars represent one standard deviation.

systems, and the current did not decrease over the 6 weeks of the experiments. For plastic-ex-1 (Pipe 2a), the average galvanic current during the stagnation periods was about 18  $\mu\text{A}$ , and plastic-ex-2 (Pipe 4e) had a much higher galvanic current of about 40  $\mu\text{A}$  (Figure 3.32). The difference of the galvanic current may be due to the properties of the pipes. Interestingly the two pipes behaved almost identically before the external connection was made, but one of the pipes (Pipe 4e in the plastic ex-2 experiment) was much more susceptible to galvanic corrosion upon the connection; differences in the structure and spatial distribution of scales of corrosion products on the pipes could be responsible for the observed differences. Although galvanic current was observed for both of the pipe assemblies, enhanced lead release was only observed for the plastic-ex-2 system. These results suggested that there may be a threshold value of galvanic current that would enhance lead release from the aged lead pipes. In this hypothesis, below this threshold value the lead produced in the galvanic reaction may stay bound on the pipe surface, while galvanic currents above the threshold value result in lead release to the water.

The measurement of current gives an indication of the amount of lead oxidized from the elemental (i.e., unaltered lead pipe) oxidation state of 0 to the +II oxidation state. Even for the pipe which displayed lead release to solution, less than 5% of the total oxidation that occurred resulted in lead release to solution; the remaining Pb(II) was apparently sequestered in the pipe scale. Observed lead release that was lower than the total amount of lead(0) oxidation to lead(II) that is predicted from the galvanic current was also observed in previous studies (Cartier et al 2012; Triantafyllidou and Edwards 2011).



**Figure 3.33 Total lead concentration after 6 hours of stagnation from experiments with Washington, DC, lead pipes connected to copper tubing using (a) plastic, (b) plastic with external galvanic wires, (c) brass dielectric, and (d) brass compression couplings. The x-axis labels indicate the week of the 6-week experiment (i.e. “W1” is Week 1).**

By connecting lead pipes and copper tubing using brass dielectric couplings, the lead and copper are not galvanically connected. However, total lead release was much higher than those from the plastic-coupled system, suggesting that sources other than galvanic interactions between lead and copper may contribute to the enhancement of lead release. Since brass and lead can also act as galvanic couples with lead serving as the anode, the enhancement of lead release may be attributed to the galvanic reaction between lead and brass. When the lead and copper were connected by brass couplings, galvanic reactions between both lead and copper and lead and brass could occur simultaneously, and their combined action may be the cause of the brass-coupled systems having the highest observed lead concentrations.

#### *Effect of Time Following Connection to Copper*

The average total lead concentrations in the effluent after the 6-h stagnation periods of each week are shown in Figure 3.33. The lead concentrations using plastic couplings were quite stable around 10 – 15  $\mu\text{g/L}$  from Weeks 1 to 6, and the duplicates matched each other very well

(Figure 3.33a). These stable results suggest that the water in the pipes may reach equilibrium with the corrosion products during the six hours of stagnation. With the external wired plastic and brass compression couplings, the effluent lead concentrations were stable over the six weeks of the experiments (Figures 3.33b and 3.33d), although as just discussed the duplicate assemblies with the externally wired connections behaved quite differently; a slight decrease in lead concentrations may have occurred in Week 6 for the brass-coupled systems.

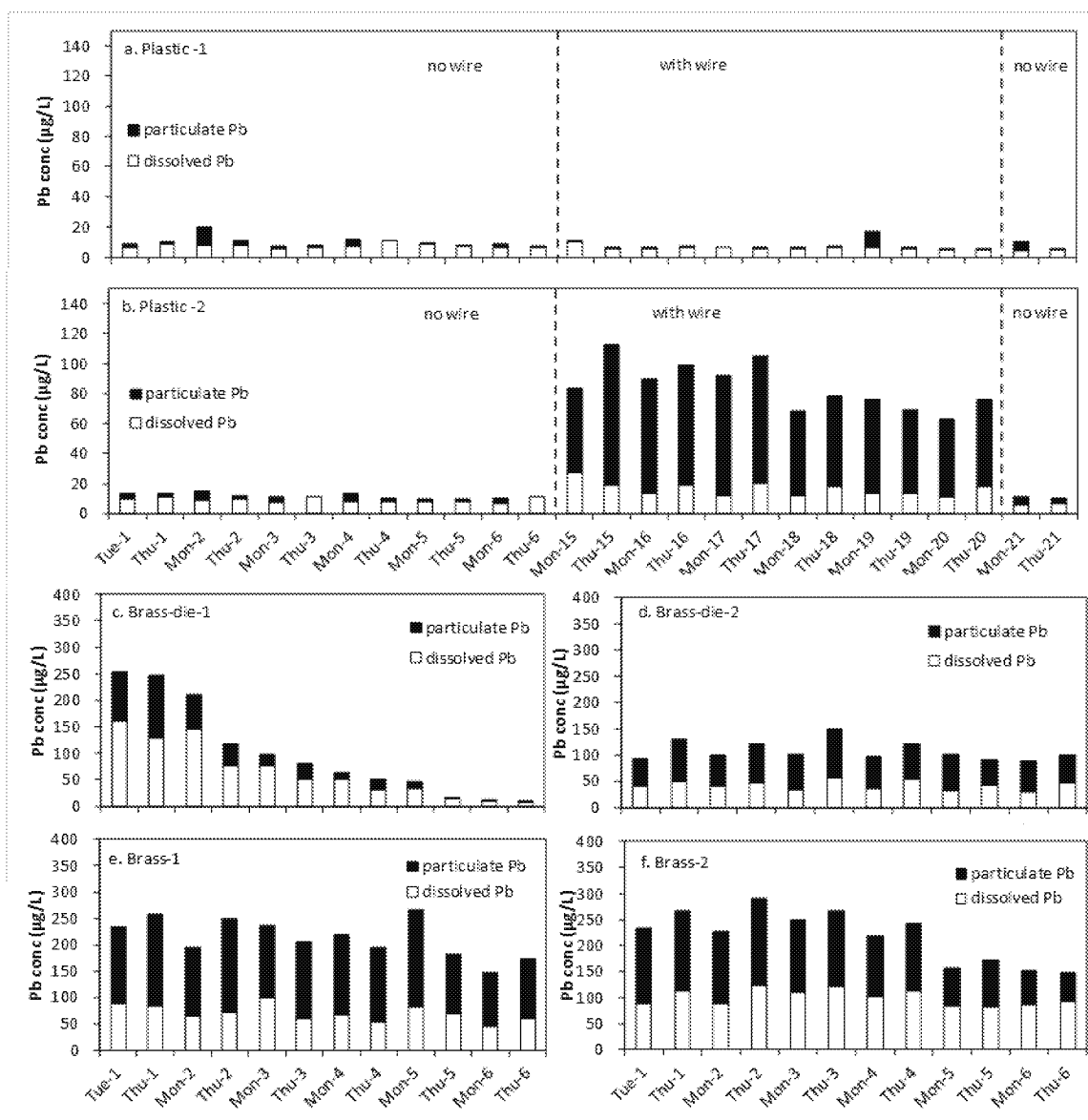
The duplicate pipe assemblies with the brass dielectric couplings also behaved differently from one another. For brass-die-2 (Pipe 4a), the effluent lead concentrations were not affected by time; while for brass-die-1 (Pipe 2b), effluent lead concentrations kept decreasing over time, from an average of 250  $\mu\text{g/L}$  in Week 1 to 10  $\mu\text{g/L}$  in Week 6. The total lead concentrations for brass-die-1 at the end of the six weeks of the experiment were comparable to those for the plastic-coupled systems, suggesting that galvanic reaction between the brass and lead for this particular pipe was transient. Enhancement of lead release was either not detected or observed as a transient effect for plastic-ex-1 and brass-die-1; these two experiments used pipe sections from the same originally harvested pipe (first digit '2'). In contrast, enhanced lead release was observed and persistent over the six weeks of the experiment for plastic-ex-2 and brass-die-2, which both used lead pipes from another address (first digit '4'). The variation of the composition and distribution of the pipe scales from different pipes may cause the difference in the observed results. Pipes 2 and 4 were harvested only two days apart from houses on the same block, and they had similar ages at the time of harvesting (105 years for Pipe 2 and 110 years for Pipe 4).

### *Distribution of Released Lead Between Dissolved and Particulate*

The distribution of total lead between particulate and dissolved was examined for all of the pipe assemblies (Figures 3.34 and 3.35). Dissolved lead was more abundant than particulate lead for the plastic-coupled systems; while particulate lead became more dominant for the brass-coupled systems, especially after longer weekend (denoted "Wknd") stagnation periods. When the externally wired connection was made for plastic-ex-2, the increased lead concentration was primarily in the form of particulate lead. Particulate lead may be the main source of lead release due to galvanic reaction between lead and copper. Because the external connections were made to the same pipes used with the regular plastic coupling connections, this increase can be seen directly in Figure 3.34. For the systems with brass dielectric couplings, both dissolved and particulate lead concentrations were higher than those for the plastic-coupled systems, and the concentrations of the dissolved and particulate lead were comparable.

For both of the pipe assemblies connected using low-lead brass couplings (Figure 3.35), particulate lead was more abundant than dissolved lead, suggesting that galvanic corrosion primarily enhanced particulate lead release. For low-lead brass-2 (i.e. Pipe 4b), increasing the stagnation time from 6 hours to 65 hours significantly increased particulate lead release, while the increased stagnation time only slightly enhanced dissolved lead release. In contrast, for low-lead brass-1 (i.e. Pipe 1) increasing stagnation time had relatively little effect on the release of either particulate or dissolved lead.

The high level of particulate lead in the pipes, especially with brass and external wired plastic couplings, may be due to two reasons. The first is the creation of local dissolved lead concentrations that were high enough to exceed the saturation of some lead(II) minerals, thus causing the precipitation of secondary solids and increasing particulate lead. The second is the



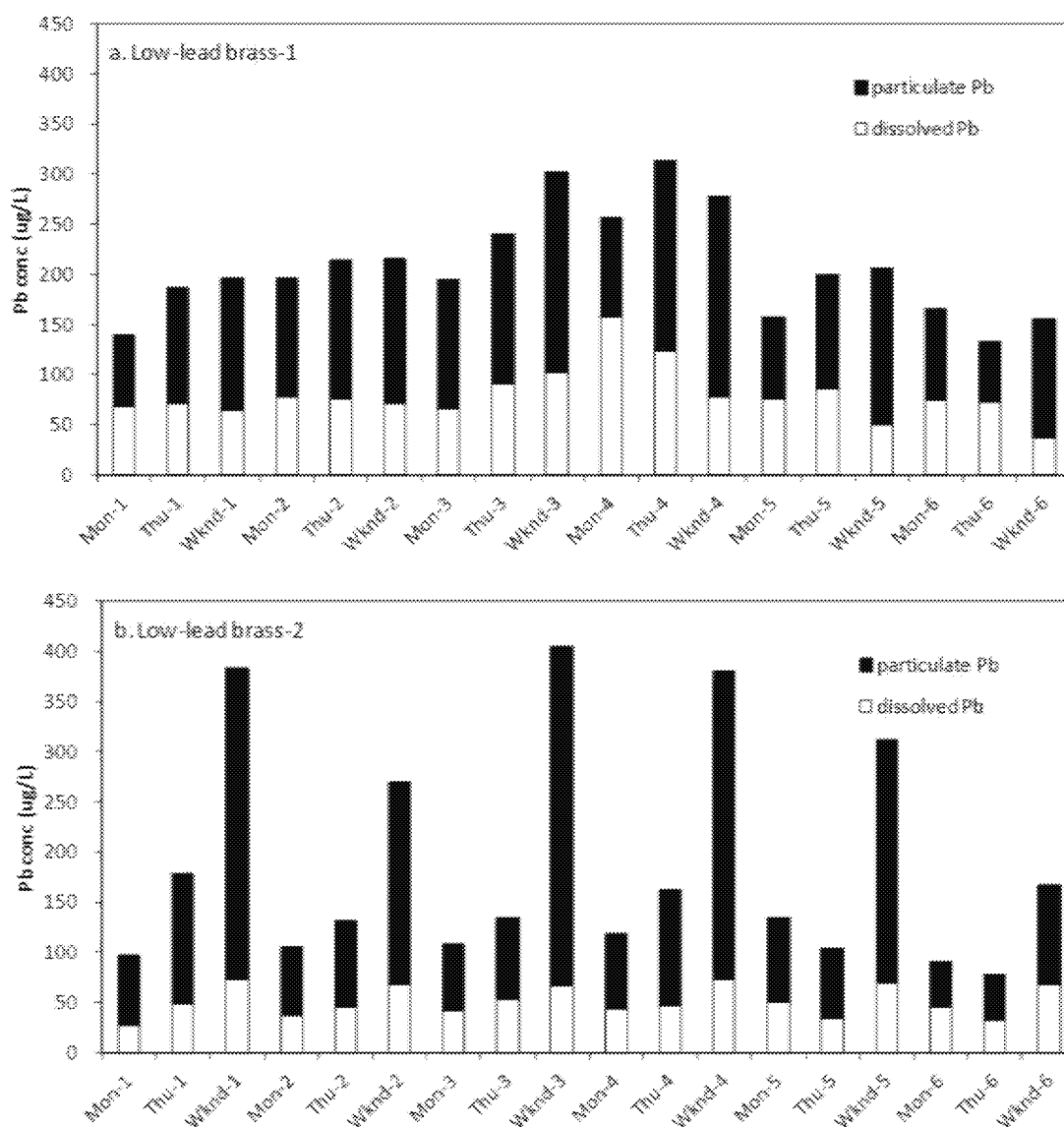
**Figure 3.34** Distribution of lead between dissolved and particulate forms for Weeks 1 to 6 of experiments with Washington, DC, lead pipes connected to copper tubing following 6-h stagnation periods using (a-b) plastic (with and without externally wired connections), (c-d) brass dielectric, and (e-f) brass compression couplings. The labels on the x-axis indicate the day of the week and the week of the experiment.

destabilization of the pipe scales that could cause portions of the scales to break off and be released to the water.

In recirculating pipe loop systems, particulate lead may accumulate in the reservoirs by adsorption to the walls or deposition to the bottom of the reservoirs during the recirculation periods and following stagnation periods for which samples were not collected. The water in the reservoir after 1 week of recirculation was acidified and its lead concentration was compared with that of the reservoir prior to acidification to determine the total lead that had accumulated in



the reservoir. The concentration of the water in the reservoir prior to acidification is the same as



**Figure 3.35** Distribution of lead between dissolved and particulate forms following stagnation periods during Weeks 1 to 6 of experiments with Washington, DC, lead pipes connected to copper tubing using low-lead brass couplings. The labels on the x-axis indicate the day of the week and the week of the experiment. Weekend (Wknd) samples had 65 hours of stagnation and all other samples were after 6 hours of stagnation.

that in the last influent sample collected for the week. This influent represents the total lead that was sufficiently mobile to be recirculated.

For the plastic-coupled systems, the total lead concentrations were a bit higher than those prior to acidification, indicating that some particulate lead had accumulated (Figure 3.36). In contrast, for the brass-, brass dielectric-, and one of the external wired plastic-coupled systems, the total lead concentrations in the acidified reservoir were much higher than those prior to